

EDGE HILL UNIVERSITY

**Optimising the use of GPS technology to quantify
biomechanical load in elite level soccer**

**Being a Thesis submitted for the Degree of Doctor of Philosophy
in Edge Hill University**

by

Pantelis Demopoulos

September 2016

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Abstract

Application of GPS technology in elite level soccer is a growing area of research. This thesis comprises an examination of current practice in elite youth level soccer, and a critical examination of the potential applications in the PlayerLoadTM measure to quantify the biomechanical demands of match play. The thesis comprises four experimental studies that consider the development of monitoring biomechanical intensity in training and/or competitive matches.

The first experimental study provides a critical examination of the biomechanical specificity of training drills relative to competitive match play. This study utilised the performance metrics as collated on a daily basis by the football club. Specifically, in relation to tri-axial accelerometry the measurement of PlayerLoad was restricted to total accumulated loading. Additional parameters related to distance and velocity parameters were also examined. ‘Small-Sided Games’ generated similar values to 90-min matches for PlayerLoad (standardised for duration) and total distance covered. However, these drills failed to provide a valid demand in terms of high-intensity running, which was most valid in ‘Movement Pattern’ drills. Drills described as ‘Possession’ and ‘Game-Related’ failed to match the mechanical demands of match play. The implications of these findings relate directly to the micro-design of the training week, and the monitoring of player performance. The correlation between PlayerLoad and distance covered was stronger in small-sided games ($r=0.92$) than in regulation 11 vs 11 match play ($r=0.37$), highlighting mechanical issues in the calculation of PlayerLoad. The smaller pitch size is likely to promote a greater frequency of speed and or directional change, and as such the summation principle applied to generate a “total” or 3-dimensional loading value is limited.

In the second experimental study the analysis of tri-axial accelerometry was extended to provide a uni-axial consideration of PlayerLoad. Biomechanically, this is analogous to analysing each force vector rather than the development of a “total” kinetic parameter based on a summation principle. This uni-axial analysis of mechanical loading was first applied to the influence of playing age via a comparison of the U16, U18 and U21 squads within the same club. The U16s performed the greatest total distance, primarily in the lower speed zones. Correlation between PlayerLoad and total distance ranged from $r=0.26-0.56$, for the three age groups, with evidence of higher coefficients in the U16 group. The U18s exhibited the greatest PlayerLoad, evident in each movement plane. Uni-axial analysis highlighted a higher contribution from medio-lateral loading in the U18s, indicative of greater lateral movement. This finding might also relate to the higher injury incidence observed in this U18 age group. The practical applications of this study relate to the transition of players through the academy structure and into senior football. The unique movement patterns identified by a uni-axial analysis of PlayerLoad highlights potential in the greater analysis of movement.

This uni-axial analysis was extended in the third experimental study to further examine issues in the movement profile with a consideration of the influence of playing position on mechanical loading. Whilst not generalisable beyond this team and playing strategy, attackers covered the greatest (total and high speed) distance, whilst midfielders exhibited the greatest load across all movement planes. Correlation between PlayerLoad and total distance was position specific, forwards and midfielders recorded values of $r=0.74$ and $r=0.16$ respectively. Playing position categorising defenders, midfielders and attackers failed to identify the impact of positional width on the biomechanical demands of match play. The traditional grouping of playing units might therefore be considered in terms of individualising training programmes. The distinction between distance covered and PlayerLoad is consistent throughout the first three experimental studies, with a low correlation in part explained by the calculation used to

quantify PlayerLoad. In the final experimental study the PlayerLoad calculation is critically examined beyond the uni-axial nature of acceleration. Having previously examined the summation principle, the failure of the PlayerLoad calculation to consider magnitude of acceleration is examined. The instantaneous change in acceleration is not influenced by the magnitude of acceleration, and in the final study a novel *i*Load parameter is introduced which is analogous to the iEMG parameter utilised widely in electromyography. This parameter considers the integral of the acceleration-time curve. Further, the sign principle is critically examined, with the PlayerLoad calculation negating all negative values and thus making all movements forward, to the right, and upward. By considering both positive and negative values the tri-axial accelerometer has the capacity to differentiate between medial and lateral movement for example, with clear implications for the monitoring of performance and injury risk. This novel biomechanical analysis was applied to an examination of fatigue during match play, which has implications for both performance and injury. Over 15min segments of match play, fatigue did not influence the antero-posterior or medio-lateral loading but there was a significant decrease in vertical load. There was also evidence of movement asymmetry in each plane, favouring movements forward and to the left. Correlation between *i*Load and total distance was $r=0.19$.

In conclusion, the thesis evaluated PlayerLoad and critically discussed the mechanical specificity of training activities. Furthermore, use of uni-axial load highlighted differences in positional demands and the influence of age group on GPS variables. Critical evaluation of PlayerLoad calculation aimed to highlight the deficiency of tri-axial acceleration of the formula. Thus, *i*Load further developed calculation to refine movement quality data to examine fatigue. By adopting principles analogous to kinetic analyses in force platform and electromyography, additional analysis parameters may be defined which provide greater depth

of information in movement quality. The implications in movement asymmetry also have implications for the monitoring of injury risk.

Acknowledgements

First and foremost, I want to thank my parents for all their support. It has been a rewarding experience to be Dr. Matt Greig's PhD student. I appreciate all his contributions. He taught me both consciously and unconsciously how rigorous scientific analysis is done. I am grateful for Dr. Lars McNaughton for providing a productive and stimulating experience. I am also grateful for Dr. Chris Carling whose feedback aided specific research questions.

CHAPTER 1. Introduction

1.1 Introduction

Jean Pierre Meerssman was the director of the Milan Lab, a high tech interdisciplinary scientific research centre that provides technological support for AC Milan. In an interview discussing the future of player monitoring he explained that, “We are trying to make a system that may say: ‘Now you will run 100 m. You will rest 43 seconds, then run 80 m, stop for one minute two seconds, and then run 61 m’ (Kuper, 2008). Such sport specific guidelines according to Meerssman will provide the athlete with the optimal training methods. To achieve this it is prudent to utilise the advances in technology that have created new methods of assessing movement patterns in soccer, including global positioning systems (GPS; Coutts and Duffield, 2008; Edgecomb and Norton, 2006; Kirkendall, Leonard and Garrett, 2004).

Global Positioning System technology has been used in numerous sports including Australian rules football, soccer, cricket, netball and field hockey (Boyd, Ball and Aughey, 2011; Castellano et al., 2011; Dunbar et al., 2014; Jennings et al., 2010; Petersen et al., 2009; Randers et al., 2010). GPS generates player information in real-time (Dawson et al., 2004), utilising coordinate location data to quantify displacement. Derivatives of distance travelled thereby enable calculation of speed, such that distance can be quantified across different speed zones (Abt and Lovell, 2009). Global Positioning System technology has evolved from early 1Hz devices (Coutts and Duffield, 2008; Duffield et al., 2010; Gray and Jenkins., 2010; Jennings et al., 2010; Portas et al., 2010) to contemporary 10Hz versions (Akenhead et al., 2014; Akenhead, et al., 2013; Rampinini et al., 2015; Varley, Fairweather and Aughey, 2012). The increased sampling frequency has enhanced validity, particularly given the highly intermittent nature of sports such as soccer. The higher sampling frequency offers greater potential to identify the rapid and acyclical changes in movement observed during soccer activities (Andersson, Ekblom and Krstrup, 2008; Di Salvo et al., 2007; Krstrup et al., 2005; Mohr et

al., 2008; Mohr, Krstrup and Bangsbo, 2003; Rampinini et al., 2007a; Rampinini et al., 2007b; Rampinini et al., 2009; Rienzi, et al., 2000).

The intermittent activity profile of soccer is further complicated by the multi-directional demands of locomotion. Micro-technologies incorporated within contemporary GPS units, such as tri-axial accelerometry, provide an even higher sampling frequency and the potential to investigate the intermittent and multi-directional movement pattern. Acceleration of the unit is measured in each of the three directional planes (Carling et al., 2008), at a sampling frequency of 100Hz. This sampling frequency is comparable to that used in alternate biomechanical analysis techniques such as motion analysis. Thus whilst a 10Hz system might suffice for changes in gross measures such as distance covered, a tri-axial analysis of movement at 100Hz offers far greater scope for an examination of movement quality. Movement quality, in terms of locomotion in each directional plane, might have implications for further understanding the mechanical response to soccer-specific activities, with implications for both performance and fatigue.

Data collected from GPS-based tri-axial accelerometry has been used to quantify a parameter defined as PlayerLoadTM, which has been adopted as a biomechanical measure in studies that examine intensity in soccer and other intermittent team sports (Barron et al., 2014; Cormack et al., 2013; Page et al., 2015). PlayerLoadTM is calculated as a summation of changes in acceleration in all three planes using the following equation:

$$\text{PlayerLoad} = \sqrt{\frac{((ay_{t=i+1} - ay_{t=i})^2 + (ax_{t=i+1} - ax_{t=i})^2 + (az_{t=i+1} - az_{t=i})^2)}{100}}$$

where

ay = acceleration in the antero-posterior (“forward”) plane

ax = acceleration in the medio-lateral (“side”) plane

az = acceleration in the vertical (“up”) plane

t = time

1.2 Statement of the Problem

Global Positioning System technology is increasingly being utilised to monitor the physical response to both training and competition. The GPS unit enables the quantification of parameters such as distance covered, and derivatives in speed, at a frequency of up to 10Hz. The tri-axial accelerometry incorporated within the GPS unit enables data collection at 100Hz (Cormack et al., 2014; Terje et al., 2016). Assuming that player mass is constant, Newton's 2nd Law dictates that force is equal to acceleration. Thus tri-axial measurement of acceleration at 100Hz offers the same potential as force platform analysis, used widely in sports biomechanics in relation to both performance enhancement and injury prevention (Yeadon and Challis, 1994). However, the ecological validity of traditional biomechanical measures of external kinetics are limited by a laboratory setting. Global Positioning System-based tri-axial accelerometry offers, therefore, the potential to conduct high-frequency, multi-planar analyses of movement in a field setting. This potential greatly enhances the use of such technologies beyond the contemporary use of 10Hz GPS measures of distance covered.

The choice of data collection technique will inevitably be influenced by the research question. In considering the physical response to training on a daily basis at a professional club, GPS-based measures might suffice. Tri-axial accelerometry offers greater scope for analysis in finer markers of movement quality. At its simplest level, a player could score an equivalent value of PlayerLoad from a match, a vertical plyometric session, or a long constant-velocity run. Fundamentally each of these sessions are unique in their movement quality, but this is lost in the calculation of PlayerLoad. The summation of directional vectors to a total value negates the relative contribution of each plane. Similarly, squaring the value in any axis negates the opportunity to explore differential magnitude in anterior (forward) and posterior (backward) movement. This would be analogous to summing the tri-axial vectors in force platform analysis, to determine a 'total' ground reaction force, which is fundamentally flawed.

Negating the difference between pronation and supination for example, and the relative magnitudes of tri-axial vectors would substantially reduce the potential of such analyses in sports biomechanics. Acceleration, as a vector quantity, has both magnitude and direction. Calculations based on tri-axial accelerometry should therefore not negate either factor.

1.3 Aims of the Thesis

In the context of a professional football academy, the thesis aims to investigate the functions of GPS-based micro-technologies in relation to:

- The specificity of training drills in relation to match play, utilising gross GPS measures including distance covered and PlayerLoad.
- The efficacy of uni-axial PlayerLoad to identify changes elicited by player age (U16, U18, U21) and position (critically examining the categorisation of positions), in addition to distance covered measures.
- A critical examination of the PlayerLoad calculation to examine the influence of fatigue during match play.

Throughout the thesis the application of tri-axial accelerometry to calculate PlayerLoad is considered in specific reference to the research question. The validity of training drills, the continuity of match-performance across the age groups akin to a club ‘culture’, the necessity for greater individualisation of positional-specific training, and the influence of fatigue on match performance are questions central to the football club at the outset of this research project. The thesis aims to explore the means of best answering such applied questions.

Chapter 2. Review of Literature

2.1 Introduction

The thesis aims to provide insight into soccer performance monitoring through the utilisation of portable GPS units in an elite sport setting. Specifically, the functions of GPS-based micro-technologies will be examined in relation to (1) the specificity of training drills in relation to match play, (2) the efficacy of uni-axial PlayerLoad to identify changes elicited by player age and position, and (3) the influence of fatigue during match play through critical analysis of the PlayerLoad calculation. This chapter explores the research that has been carried out in soccer, specific to the target population in the thesis. The review first considers the myriad of data collection and analysis techniques that have been used in the performance monitoring of team sports, including the contemporary developments in GPS technology and the subsequent development of performance metrics. The previous applications of GPS-based micro-technologies in soccer training and coaching are then reviewed, along with a consideration of issues in validity and reliability of GPS-based micro-technologies in team sports. Methodological elements of previous research are presented in order to justify the approach of analysis adopted for this research project.

2.2. Performance monitoring in team sports

Soccer is characterised by an intermittent, multi-directional and irregular activity profile, which increases the complexity of both the physiological and biomechanical response (Greig, McNaughton and Lovell, 2006). The evolution of monitoring systems has resulted in a broadening of analysis parameters from the earliest notation systems. Subsequently, the examination of 'performance' has also evolved to include quantifiable measures of the physical response to match play and training. This physical response has largely been considered in terms of physiological response, with biomechanical intensity having received less attention

2.2.1 Performance measures

Whilst this thesis utilises GPS data to quantify the biomechanical response to training and match play, a variety of different monitoring systems have been used to quantify performance. Studies using multiple-camera computerised tracking technology have previously been utilised to summarise the performance demands of soccer. One of the most commonly analysed performance metrics is distance covered. Di Salvo *et al.* (2007) examined the performance characteristics in soccer with reference to position played. Three hundred outfield players were monitored over 30 matches during the 2001/2 and 2003/4 seasons (20 Spanish La Liga matches and 10 Champions League games) using a multiple-camera match analysis system (Amisco Pro[®], version 1.0.2, Nice, France). Examining the work-rate profiles of elite soccer players it was reported that the mean distance covered over 90-minute match play was 11393 ± 1016 m (Di Salvo *et al.*, 2007). Central and External midfielders (CM & EM) covered significantly greater distance ($p < 0.0001$) than both defender groups as well as the attackers (12027 m and 11990 m compared to 10627 m, 11410 m and 11254 m). The observation of midfielders covering the greatest total distance has been supported in more recent analyses (Bojkowski *et al.*, 2015; Bradley *et al.*, 2009; Cihan, Can and Seyis, 2012, Duk *et al.*, 2011; Mallo *et al.*, 2015). Bradley *et al.* (2009) reported that during a 90-minute soccer match in the Premier League midfielders run on average 11459m. However, Mohr, Krustup and Bangsbo (2003) and Rampinini *et al.* (2007b) recorded wide defenders and attackers as the positions covering greater distance than midfielders. In these studies, the midfielders (central and wide) were placed under the same category, and thus when comparing notational analyses, the categorisation of playing position is critical when analysing performance profiles. In the present thesis an examination of position-specific demands includes distance covered as a performance measure, but considers the sensitivity of playing position categorisation beyond a traditional consideration of defender, midfielder, attacker.

The influence of playing position has also been observed in relation to other performance measures such as high-speed running and agility. Di Salvo *et al.* (2007) reported that central midfielders covered the greatest distance at a speed band of 11.1-19 km·h⁻¹. Di Salvo, Barron and Gonzalez-Haro (2010) conducted a sprinting analysis of elite soccer players during Champions League and UEFA Cup matches in order to evaluate the differences in relation to playing position. Prozone[®] video analysis (Version 3.0, Prozone[®] Sports Ltd., Leeds, UK) was used to quantify distance covered by each of the 717 outfield players that took part in 67 matches over four seasons (2002-2006). This was the first study to focus on specific sprinting activities (>25.2 km·h⁻¹) during European matches. The main findings of the study showed that wide midfielders accumulated significantly more sprints (35.8 ± 13.4 , $p < 0.001$, $d = 0.46-1.64$), followed by attackers (30.0 ± 12.0) and wide defenders (29.5 ± 11.7). Central midfielders and central defenders performed 29.5 ± 11.7 and 17.3 ± 8.7 sprints respectively. Gregson *et al.* (2010) analysed English Premier League Data over three seasons (2003-2006) and found central midfielders recorded highest number of sprints (41 ± 13) with attackers, wide defenders, central midfielders and central defenders covered fewer sprints respectively (34 ± 13 , 34 ± 12 , 30 ± 13 , 20 ± 9). This data agrees with the findings of previous studies (Bradley *et al.*, 2009; Di Salvo *et al.*, 2007; Leventer *et al.*, 2016). The values recorded for distance covered and high-speed running seems to highlight the differences in the activity profile between positions (Currell and Jeukendrup, 2008).

Reilly (2003) also suggested that sprint capacity of players is directly linked to their position, and high-intensity running as a measure of physical performance has shown to be a strong indicator of different standard of player (Abrantes, Maças and Sampaio, 2004; Bangsbo, 2014; Bangsbo, Nørregaard and Thorsø 1991; Mohr, Krstrup and Bangsbo, 2003). More contemporary analyses also support a change in the demands of soccer. With the use of Prozone player tracking (Prozone Sports Ltd[®], Leeds, UK) over the course of seven seasons

(2006-2007 to 2012-2013) it was concluded that both high-intensity running and total sprint distance increased ($890 \pm 299\text{m}$ in 2006-2007 to $1151 \pm 337\text{m}$ in 2012-2013, $p<0.001$, $ES=0.82$; $232 \pm 114\text{m}$ in 2006-2007 to $350 \pm 139\text{m}$ in 2012-2013, $p<0.001$, $ES=0.93$, respectively) underlining the importance of high-intensity actions as stated above (Barnes et al., 2014). Load was not reported in this study and is an example of the limited biomechanical analysis afforded in soccer to date.

Computerised time-motion video-analyses have also been used to quantify the physical demands of different positions in the FA Premier League in relation to movement patterns (Bloomfield, Polman and O'Donoghue, 2007). Data gathered from 55 outfield players across 12 teams is summarised in Table 2.1, highlighting the influence of player position on direction of travel.

Table 2.1. Percentage time of direction travelled by players of different positions. Data are means (\pm SD).

Variables	Striker (n=19)	Midfielder (n=18)	Defender (n=18)	All (n=55)
Directly forwards	46.9 (10.1)	54.1 (7.5)	45.3 (7.7)	48.7 (9.2)
Directly backwards	5.6 (2.7)	5.2 (2.8)	10.1 (3.5)*	7 (3.7)
Lateral left	3.7 (1.6)	3.4 (1.4)	6.5 (2.9)*	4.5 (2.5)
Lateral right	3.5 (1.6)	3.2 (1.7) ‡	5 (3) ‡	3.9 (2.3)
Forward diagonal left	4.5 (1.7)	4.9 (2)	4.5 (2.2)	4.6 (1.9)
Forward diagonal right	4.5 (1.7)	4.4 (2.7)	5.1 (2.9)	5 (2.6)
None	24.4 (6.6)*	18.8 (5.1)	18.3 (7)	20.6 (6.8)

*significantly different to both other positions, ‡ pair of positions annotated is significantly different

Midfielders were observed to perform the most directly forward movement while defenders gather the highest backwards and lateral movement. The majority of diagonal movements were distributed amongst midfielders and forwards. Since these positions usually require such

direction in order to create space or avoid a defender in a short space of time due to the variability and unpredictability of the sport (Nicholas, Nuttal and Williams, 2000; Wragg, Maxwell and Doust, 2000). The study also included the frequency of turning and swerving performed by players, which is summarised in Table 2.2. More contemporary analyses also support the locomotive differences between external and central defenders. It was found that external defenders performed significantly more backwards movements ($p=0.002$) than central defenders (Ali, Spendiff and Brouner, 2016).

Table 2.2. Frequency of turning and swerving within a match performed by players of different positions. Data are means (\pm SD).

Variables	Striker (n=19)	Midfielder (n=18)	Defender (n=18)	All (55)
0-90° right	324 (105)	248 (97)*	344 (91)	306 (105)
0-90° left	302 (81)	243 (94)*	364 (89)	303 (99)
90-180° right	43 (16)	49 (25)	43 (17)	45 (19)
90-180° left	52 (14)	47 (25)	49 (21)	49 (20)
180-270° right	3 (4)	5 (4)	2 (3)	3 (4)
180-270° left	2 (4)	3 (5)	2 (3)	2 (4)
270-360° right	1 (3)	1 (2)	0	1 (2)
270-360° left	1 (2)	2 (4)	0	1 (3)
Swerve right	9 (8)	6 (7)	8 (6)	7 (7)
Swerve left	12 (10) ‡	4 (7) ‡	9 (10)	9 (10)
Total	748(173)	608 (207)*	822 (175)	727 (203)

*significantly different to both other positions, ‡ pair of positions annotated is significantly different

Overall, the players monitored, performed 727 ± 203 turns during match play with turns to the left or right of 0 to 90° amounting to 609 ± 204 . In contrast to the observation of greater distance covered by midfielders, these players performed the least number of turns. Considering physical conditioning, players in different positions would benefit from specific programmes i.e. defenders and strikers could adopt speed and agility drills and midfielders could practice

interval training over longer distances (Bloomfield, Polman, and O'Donoghue, 2007).

The examination of activity profiles in relation to performance measures such as distance covered and frequency of turns has important implications in the profiling of players, and particularly in developing specific positional demands. Many of these notational analyses have been applied to elite match play, but despite the high level of ecological validity the studies are typically limited in providing a more rigorous interpretation of physical demands. Until very recently there has been little opportunity for the collection of physiological or biomechanical data during competitive matches.

In contrast to the camera-based systems, the development of portable GPS-based systems has enabled the analysis to include additional metrics associated with location. The coordinate based measurement of distance travelled enables differentials in velocity profiling to be examined. The GPS-based systems that contain tri-axial accelerometry have further enabled the measurement of acceleration across the three primary planes of movement. Through assessing physical load of performance research can provide findings on the movement intensity profile of each playing position as it has been done with total distance. Whilst previous studies have identified the influence of playing position on distance covered (Bradley et al., 2009; Cihan, Can and Seyis, 2012; Di Salvo et al., 2007), the impact on physical and biomechanical demands was not developed.

The analyses of distance covered in different speed zones (Di Salvo, Baron and Gonzalez-Haro, 2010) would apply well to the analysis capabilities of GPS-based micro-technologies such as tri-axial accelerometry and the associated metric of PlayerLoad. The acceleration and deceleration within the speed zones will accumulate PlayerLoad, and as such PlayerLoad is also likely therefore to be position-specific. Sprinting requires acceleration capability and PlayerLoad is measured via accelerometry. Therefore, acceleration and load are linked and sprinting is position-specific. Similarly, analysis of turns highlights the multi-directional nature

of the activity profile, which is well suited to the tri-axial capability afforded by many GPS systems. This is analogous to an external kinetic analysis as performed using force platforms in a laboratory. A change of direction will produce a change in acceleration, and thus an accumulated PlayerLoad. The tri-axial capacity would therefore enable a measure of PlayerLoad in each movement axis, with implications not only for performance but also potentially in injury.

The findings of Di Salvo, Baron and Gonzalez-Haro (2010) present the variations of the physical demands on a squad based on positional roles and this can be used by the coaching staff when devising training sessions to ensure each player is training with position specific drills. Bradley *et al.* (2009) advocated quantifying sprinting load on the body because sprinting has been correlated to PlayerLoad as accelerations and decelerations out of high-speed actions accumulate load. It would be useful to have reported data on PlayerLoad over the seasons also. The opportunity then would be given to conclude as to whether or not the biomechanical demands have increased similarly to distance and sprinting.

Research has shown that the match demands of elite Australian Football (AF) agrees with the previous findings in soccer that players fatigue during matches and use a pacing strategy to moderate fatigue experienced later in matches (Bradley *et al.*, 2009; Coutts *et al.*, 2010; Duffield, Coutts, and Quinn, 2009; Mohr, Krstrup and Bangsbo, 2003; Rampinini *et al.*, 2007a). In addition, studies have shown that the running demands of AF players have increased in the past few years, with a 7% increase in both mean running speed and steady-state running over $8 \text{ km} \cdot \text{h}^{-1}$ from the 2005 to 2008 seasons (Wisbey *et al.*, 2010). Aughey (2010) recorded 147 match profiles of 18 AF players during the 2008-2009 seasons. Global Positioning System with a 5Hz frequency was used for the first time in this study of AF. The results showed that the players managed to maintain total distance and low intensity activity throughout the matches. Another finding of this study was that there were small reductions in high intensity

running in the latter part of the matches. This could be a result of the rotations carried out throughout the course of the matches giving the players the time to recover from their intense bouts of exercise while on the pitch.

Sustaining performance during soccer is fundamental to the physical development of players. Monitoring fatigue in soccer has been researched in order to properly assess the cause of the decline in physical performance during match play. Mohr, Krstrup and Bangsbo (2003) showed that performance declines in the first 5 minutes of the second half in comparison to the same period during the first half. Research has shown declines in accelerations ($9 \pm 8 \%$, $p=0.004$) and decelerations ($9 \pm 8 \%$, $p=0.005$) when analysing each 45-minute half of play.

Through the computerised time-motion analysis, of 18 professional soccer players during a competitive season, it was concluded that high-intensity running decreased during the second half of match play (Mohr, Krstrup and Bangsbo, 2003). A similar study conducted at youth level analysed total distance covered during each half and running speed with the use of GPS (Lovell, et al., 2009). Thirteen youth team players (16-18 years old) representing an English League One club wore 5Hz GPS (MinimaxX, Catapult, Australia) units in 10 competitive games during the 2008/2009 season. The three speed thresholds were categorised as follows: high-intensity running (HIR; $14 - 35 \text{ km}\cdot\text{h}^{-1}$), very-high intensity running (VHIR; $19 - 35 \text{ km}\cdot\text{h}^{-1}$) and sprinting ($25 - 35 \text{ km}\cdot\text{h}^{-1}$). Total distance covered amounted to $8830 \pm 816 \text{ m}$, 18% ($1575 \pm 416 \text{ m}$) at HIR, 11% at VHIR ($794 \pm 282 \text{ m}$) and 1.4% of total distance at sprinting velocities ($125 \pm 76 \text{ m}$). In the second half total distance decreased by 18% compared to the first half. Similar decrements were recorded for the speed thresholds also, HIR 20%, VHIR 20% and sprinting 24%. Contemporary analysis of English FA Premier League Players recorded comparable results with a decline of 4.7% and 12% in total distance and high-intensity running respectively (Bradley and Noakes, 2013). When assessing differences in performance during the initial 15 minutes of match play and the corresponding time frame during the second half

the reductions were noticeable in HIR (284 ± 100 m and 231 ± 106 m), VHIR (155 ± 79 m and 116 ± 73 m) and sprinting values (28 ± 32 m and 16 ± 17 m). During the initial 15 min of the second half HIR, VHIR and sprinting showed a decrease of 62, 67 and 100% of total second half decrement in performance (Lovell, et al., 2009). Thus, total distance in youth soccer is lower than the values generated by professional players (Di Salvo et al., 2007) albeit quantified through Prozone[®]. The proportions of high-intensity were comparable to other studies (Di Salvo, Barron and Gonzalez-Haro 2010), however the biggest decrements in performance were recorded in the initial period of the second half in contrast to previous studies that reported decreases during the final 15 minutes (Bangsbo, 1994; Bangsbo, Nørregaard and Thorsø, 1991; Mohr, Krstrup and Bangsbo, 2003; Reilly and Thomas, 1976; Rienzi et al, 2000). Therefore, the study revealed that total distance and high-intensity running were markedly lower in the second half, findings that are in agreement with previous studies (D'Ottavio and Castagna, 2001; Rampinini et al., 2007b; Weston et al., 2007). The decrements in performance recorded could be a result of the age group of players. A method to address this decrement in performance recorded in the initial stages of the second half could be the introduction of exercise drills during the half time between 90-minute match play.

Research has presented an evolution in the physical capacity of soccer players (Barnes et al., 2014) namely through the development of acceleration capability. This development of physical performance has implications on the mechanical load of such actions. The studies discussed measured-markers of performance that included total distance, high-speed running, and frequency and direction of sprinting. PlayerLoad that measures the biomechanical load of accelerations, a characteristic of primary importance (Bangsbo, Nørregaard and Thorsø, 1991), could provide an alternative (or at least supplementary) measure of performance to total distance and high-speed running. With recent developments enabling collection of GPS data

during match play, with the concession of the governing body, such analyses of performance profiling could be broadly extended.

2.2.2 Physiological measures

Reasons to adopt a performance monitoring system include athlete adaptation to training practices and minimisation of non-functional overreaching (Schmikli et al., 2011) or long-term fatigue. Despite the benefits, there are instances where sport clubs do not possess the financial resources to invest in such a system in addition to hiring staff (Halsen, 2014). Rating of perceived exertion (RPE) with the use of the Borg (Borg, 1982) scale (0-10) is a method used to assess internal load that has a high correlation with heart rate (HR) in cycling training, however not as well with high-intensity soccer drills (Borresen and Lambert, 2009). Foster (1998) developed the session RPE (sRPE) as a method to monitor training load. The methodology in this case involves multiplying the athlete's RPE (0-10 scale) by the duration of the training session (in minutes). Research in soccer has reported correlations between sRPE and HR zones from $r=0.54$ to $r=0.78$ (Borresen and Lambert, 2008). This correlation magnitude highlights that heart rate is one of several factors that would contribute to total training load. The sRPE is a simple method that does not require other measurement tools like HR monitors to assess exercise intensity, however, by including additional methods of assessment sport scientists can develop an understanding of the variance in athlete sRPE scores recorded (Halsen, 2014).

A study examining youth soccer players implemented sRPE using Borg (verbal descriptors) and OMNI (verbal and pictorial descriptors) scales to evaluate performance (Rodríguez-Marroyo and Antoñan, 2015). It was concluded that during technical-tactical training sessions sRPE could properly assess exercise intensity since it has been suggested heart rate was not a good indicator of exercise intensity for plyometric, speed or intermittent training (Foster et al.,

2001; Haddad et al., 2011; Impellizzeri et al., 2004). High correlations were found between sRPE ($r=0.76$) and training load as measured by sRPE multiplied by duration and heart rate ($r=0.79$). Further, sRPE is a good indicator of internal training for ergometer protocols found in earlier studies and for soccer during tactical and technical drills as mentioned above (Marinov, Mandadjieva and Kostianev, 2008; Parfitt, Shepherd and Eston, 2007; Rodríguez-Marroyo and Antoñan, 2015; Roemmich et al., 2006; Utter et al., 2002). It has been shown that sRPE can provide information on the training load of soccer and since it does not require knowledge of software or use of other technologies it is a simple method that can provide information on performance monitoring.

In a study conducted by a Spanish first Division team, physical exertion was measured during 13 training sessions (Gomez-Piriz, Reyes and Ruiz-Ruiz, 2011). The modes of measurement were the 21-point session rating of perceived exertion (sRPE) and the total PlayerLoad (TPL) parameter of a GPS device. PlayerLoad is derived from the acceleration forces an athlete generates during an action. The quantification of this parameter is based on the tri-axial accelerometer that summates the antero-posterior (x), medio-lateral (y) and vertical (z) axes on the movement plane. Elite rugby union has used this value to evaluate the physiological demands of the sport as mentioned above (Cunniffe et al., 2009). RPE and heart rate (HR) have shown to have a high correlation, therefore the established validity of RPE was assessed in comparison to the PlayerLoad generated by a GPS unit (Foster, 1998; Foster et al., 2001; Foster, et al., 1996; Foster et al., 1995; Impellizzeri et al., 2004). Quantifying exercise training on the basis of positional differences was another aim of this study. Since research has shown that the extensive use of small-sided games in training sessions does not provide sufficient physiological adaptations for the fittest players it was hypothesised that midfielders would have the lowest values for both variables measured (Davis, Brewer and Atkin, 1992; Hoff et al., 2002; Rohde and Espersen, 1988). Twenty-two professional male soccer players of the Real

Club Recreativo de Huelva (Spanish first division; mean \pm SD: 26.74 \pm 4.2 years, height 179.74 \pm 4.04 cm, weight 73.7 \pm 3.35 kg) participated in the study of Gomez-Piriz, Reyes and Ruiz-Ruiz (2011). The sessions were comprised of a standardised warm-up, a 20-minute small-sided game (4 bouts of 4mins with 2 mins active recovery between bouts) and a standardised warming-down. The results revealed that there was a weak nonlinear relationship between RPE and TBL. The authors therefore reported that TBL cannot evaluate movement elements which might influence RPE and HR such as working with the ball, running backward, sideways and changing direction (Gomez-Piriz, Reyes and Ruiz-Ruiz, 2011). However, further analysis of the PlayerLoad calculation can provide orientation (backward running) of movement and the occurrence of change of direction. The additional analysis would provide a detailed profile of the movement pattern of soccer players. The analysis is required since the detailed movement pattern is masked with the formula of PlayerLoad (Boyd, Ball and Aughey, 2011). Computation of PlayerLoad involved use of the following acceleration zones: 5-6 g light impact, hard acceleration, deceleration or change of direction; 6-6.5 g light to moderate impact (player collision, contact with the ground); 6.5-7 g moderate to heavy impact (tackle); 7-8 g heavy impact (tackle); 8-10 g very heavy impact (scrum engagement, tackle); 10+ g severe impact, tackle or collision. The sensitivity of these thresholds is also likely to influence interpretation. Further, these acceleration zones are dictated by the software (Team AMS; GPSports, V1.2, Canberra, Australia). Interpretation of speed thresholds may change with the inclusion of individualised speed zones (Lovell and Abt, 2013). High intensity running speeds determined by second ventilatory threshold (VT(2speed)) are substantially less than what is quoted by Prozone (Abt and Lovell, 2009). Therefore, the setting of these thresholds used with acceleration zones is important.

The collection of physiological data during competitive match play is limited, and thus the majority of physiological data used to inform player monitoring is obtained during training.

Training impulse (TRIMP) is a performance monitoring tool used for the measurement of internal training load that assesses physical effort through the calculation of training duration and maximal, resting and mean heart rate during exercise (Morton, Fitz-Clarke and Banister, 1990; Pyne and Martin, 2011). Banister (1991) developed TRIMP to measure training load, a valid tool for measuring performance of endurance athletes (Morton, 1990). The initial TRIMP model (Banister and Calvert, 1980) have been developed through Edward's TRIMP, that examines accumulated duration in five arbitrary HR zones multiplied by a weighting factor and Lucía's TRIMP, that examines three zones with their thresholds based on the first and second ventilatory thresholds (Edwards, 1993; Lucía et al., 2000). Banister's TRIMP treats the exercise intensity by calculating heart rate reserve and duration (Bannister, 1991). Mean heart rate is weighted according to relationship between heart rate and blood lactate, then multiplied by duration. The application of Banister's TRIMP to intermittent sports such as soccer has two limitations. One, the use of mean heart rate may not provide a representative value of the fluctuations during soccer as mean exercise intensity has been recorded at 85% of HR max (Stolen et al., 2005) with peaks of intensities near HRmax (Ascensao et al., 2005). Second, the equation used for males and females implies that only gender results in differences recorded amongst athletes. Recently, individualised TRIMP (iTRIMP) has been tested on soccer players, that does not rely on arbitrary HR zones and generic weightings proving to be highly correlated ($r=0.67$) to changes in velocity at lactate threshold (Akubat et al., 2012). Akubat *et al.* (2012) states that heart rate monitors, calculation of iTRIMP and monitoring training load requires technical and scientific expertise and that clubs need to recruit qualified professionals to implement this system of internal load monitoring.

In a study combining internal and external training load in soccer, Akubat, Barrett and Abt (2014) incorporated iTRIMP (internal load) and GPS technology (external load) during a simulation (Ball-Sport Endurance and Sprint Test [BEAST90_{mod}]). The analysis created the

following performance ratios; total distance:iTRIMP (TD:iTRIMP) and high speed distance:iTRIMP (HID:iTRIMP). Analysis of BEAST90_{mod} revealed correlations between HID:iTRIMP and onset of Blood Lactate Accumulation ($r=0.65, p=0.04$) and TD:iTRIMP with velocity and lactate threshold ($r=0.69, p=0.03$). The findings suggest that an integrated ratio may prove more useful than measures of external load on their own. In the future, adopting this ratio during different phases of match play can provide insight into the mechanisms of fatigue in soccer (Akubat, Barrett and Abt 2014). The GPS capacity to measure distance covered might also be extended to consider the broader availability of markers of intensity, including PlayerLoad for example.

Manzi *et al.* (2013) examined the performance of elite level soccer players during pre-season training sessions through the use of TRIMPi. Testing measures involved treadmill tests for VO₂max, ventilatory threshold (VT), speed at blood-lactate concentration of 4 mmol·L⁻¹ (S4), and the Yo-Yo Intermittent Recovery Test (Yo-Yo IR1). Results showed that TRIMPi was highly correlated with percentage changes in VO₂max ($r=0.77, p=0.002$), VT ($r=0.78, p=0.002$), S4 ($r=0.64, p=0.004$), and Yo-Yo IR1 ($r=0.69, p=0.009$) respectively. This study supports the longitudinal validity of TRIMPi to measure aerobic fitness through the assessment of intensity and volume exercise through its application to soccer (Akubat, et al., 2012; Impellizzeri and Marcora, 2009; Manzi et al., 2009). In addition, average weekly TRIMPi values of >509 AU are required for improvement of endurance in soccer players making this a valid measurement when examining the dose-response relationship of aerobic performance (Manzi et al., 2013). Whilst encouraging, these observations are restricted to measures of physiological capacity in laboratory and training environments. The self-paced nature of football negates perhaps the influence of physiological capacity, as many other factors beyond capacity will influence what a player does in a game. Such observations need to be expanded to match play, as considered by research conducted by Hoff and Helgerud (2004) where a

change in physiological capacity was matched against performance metrics in match play.

The limitations imposed by competition on the collection of physiological data has, in part, been supplemented by the use of small-sided games in training, which are purported to enable coaches to address conditioning along with technical and tactical skills simultaneously (Almeida, Ferreira and Volossovitch, 2013; Hill-Haas et al., 2009; Jones and Drust, 2007). Casamichana *et al.* (2014) observed the physiological and mechanical response of 12 semi-professional players (age: 22.7 ± 4.3 years; body height: 177.5 ± 4.9 cm; body mass: 74.9 ± 6.3 kg) through manipulation of the number of soccer ball touches during small-sided games. The games were split into two six-minute periods and players were allowed 'free play' for one game and then limited to two-touch passes in the other. During the first condition there was a significant decrease in total distance covered during the second period compared to the first (716.3 ± 77.3 m vs 642.2 ± 91.1 m or -10.4%), distance covered at speeds of ≥ 18 km·h⁻¹ (-32.2%) and PlayerLoad (91.9 ± 12.9 vs 76.8 ± 13.1 or -16.4%). The two touch pass games elicited a 6.2% increase in mean heart rate during the second six-minute period ($89.3 \pm 3.1\%$ HR_{max}) compared to the first six-minute period (83.8 ± 4.3 HR_{max}). The findings showed that two touch games required a higher intensity since there was no reduction in running performance as compared to the 'free play' game. It should be noted that coaches should be aware when using small-sided games since they may promote low physiological demands since the time spent below 75% HR_{max} increases. For players to experience more representative activity patterns of game requirements (variable stimulus) coaches should implement game like situations during training sessions in addition to small-sided games (Abade et al., 2014). At present, research has provided insight into the physiological aspects of small-sided games. This research project aims at increasing knowledge on the subject by analysing various training drills both physically and biomechanically.

Performance monitoring provides athletes and coaches with information required for positional profiling. As presented in research, playing position is a distinctive factor of performance. Camera and GPS-based technologies have provided insight into distance and speed parameters. This section aimed to highlight the lack of biomechanical information, which GPS might assist with given the associated capabilities of quantifying tri-axial accelerometry. Presenting research on previous applications in GPS analyses is required to assess training and match performance including limiting parameters of fatigue and injury epidemiology.

2.3 Previous applications in GPS analyses

2.3.1 GPS analyses of training sessions

Global Positioning System technology has been used extensively in field sports (Aughey, 2011a), namely Australian football (Colby et al., 2014; Duhig et al., 2016; Kempton et al., 2015), cricket (Greig and Nagy, 2016; Petersen et al., 2009; Vickery et al., 2014), hockey (MacLeod et al., 2009; Vescovi and Frayne, 2015), rugby union (Cunningham et al., 2016; Owen et al., 2015; Reardon, Tobin and Delahunt, 2015; Swaby, Jones and Comfort, 2016), rugby league (Black and Gabbett, 2014; McLellan et al., 2011) and soccer (Gomez-Piriz, Jiménez-Reyes and Ruiz-Ruiz, 2011; Mallo et al., 2015; Portas et al., 2010; Saward et al., 2016). AF is potentially the sport GPS is being used the most, partially due to its low cost and portability in addition to the oval shape of the field making automated video camera analysis, of up to 36 players on the pitch at once, quite difficult. It could be argued that with GPS unit prices in the range of £1000 the amount spent to acquire them could make up a large percentage of the performance budget of AF teams.

Small-sided games have been analysed by GPS technology in order to monitor player performance in reference to movement patterns. In a study by Dellal *et al.* (2011a), 20

international players and 20 amateur players from the French fourth division took part in a series of small-sided games (SSGs) in order to examine the differences in physical responses, technical and time-motion activities based on the GPS (GPSports SPI Elite System, Canberra, Australia) data at a sampling frequency of 5Hz. The results showed a higher blood lactate [La] in the amateur players as a result of more directional changes and increased sprinting during SSGs. Distance and distance covered at sprint ($>18 \text{ km}\cdot\text{h}^{-1}$) was consistently higher during the 'one touch' condition for the professionals in comparison to the amateurs across all variations of small-sided games. This mode of training provides a variety of training stimuli including sprinting, change of direction, technical load and tactical activities (Bradley et al., 2009; Dellal et al., 2011a). It should be noted that only one GPS metric was used, distance with two derivatives, sprinting and high-intensity running. It seems distance is the most indicative measure of the effectiveness of small-sided games. Due to close replication of the physiological and technical match play conditions in SSGs, it is a useful training tool for elite soccer coaches. As mentioned, with the only GPS parameter measured being distance the physical response is vague with reference to the understanding of biomechanics in soccer. The study (Dellal et al., 2011a) claims to have measured the physiological, physical and technical activities of small-sided games without the inclusion of biomechanics that can be analysed through the portable GPS units. Further 5Hz GPS units produce acceptable levels of validity only at walking (SEE=9.9%) pace (Jennings et al., 2010) where small-sided games require movement with tight changes. A parameter of this research project would be to compare the game data findings gathered with similar data collected during small-sided games to record any similarities or differences in order to verify the hypothesis that small-sided games replicate match biomechanical demands.

Small-sided games also generate different GPS values when the dimensions of such drills are altered (Gaudino, Alberti and Iaia, 2014; Mara, Thompson and Pumpa, 2016; Owen et al.,

2012; Silva et al., 2014). In a study by Casamichana and Castellano (2010), GPS technology (SPI-elite, GPSports, Canberra, ACT, Australia) was used to monitor the physical performance of 10 male youth soccer players during three SSGs with a large, medium and small pitch size. During a competitive match the ratio of pitch area per player is 272.8 m^2 and the pitch sizes in the study were 272.8 m^2 , 175 m^2 , 74 m^2 , for the large, medium and small SSG respectively. Therefore, as a training tool, the dimensions represent the match play conditions. The exercise-to-rest ratio derived from the GPS data showed that on a small pitch the ratios are the lowest due to highly intermittent activity where high-intensity tasks are interspersed with moments of recovery where the player is either stationary, walking or jogging (Casamichana and Castellano, 2010). In the medium and large pitch SSGs movements were covered for greater distances at high intensity due to increased field of play. Therefore, designing football drills must assist players to increase their technical and tactical options in addition to their physical performance. The limitation of this study is the sampling rate of 1Hz that was used since the reliability for high-intensity running is relatively low. Similarly to Dellal *et al.* (2011a), the only GPS metric used in this study (Casamichana and Castellano, 2010) was distance covered at various speeds. In addition, 1Hz GPS sampling frequency can misrepresent soccer performance in relation to short distance, as typically found during small-sided games (Scott, Scott and Kelly, 2016). At a sampling frequency of 1Hz it seems suitable to measure linear distances. With the development of 10Hz GPS sampling frequency and 100Hz in accelerometry there is the opportunity for more analysis of movement in soccer. Higher sampling frequency can provide greater biomechanical analysis of soccer. The biomechanical profile of small-sided games has not been widely explored, partially due to the limited methodologies available before the inclusion of GPS technologies into soccer training. Research has revealed that small-sided games with fewer soccer players increases physiological stress while larger games can address match-specific demands (Aguiar et al.,

2013). This finding lends itself to a consideration of the mechanical demands of small-sided games, with the running profile of soccer players influenced by larger pitch dimensions. Small-sided games are used during soccer training sessions to develop technical and tactical (Almeida, Ferrera and Volossovitch, 2013) awareness whilst also developing physical conditioning as they appear to replicate requirements of competitive match play (Hill-Hass et al., 2008; Köklü, 2012; Little, 2009). Tactical awareness is an element of soccer play that has implications on positioning of players on the pitch. Hughes and Bartlett (2002) found that tactical performance indicators in soccer seek to reflect the relative importance of teamwork, pace, fitness and movement, which makes time motion variables important in order to understand this game aspect. There is large variability in player behavior on the pitch and is dependent on the interaction between players, opponents and ball possession, making it difficult to analyse with the traditional notational or motion analysis (Davids, Araújo and Shuttleworth, 2005). Folgado *et al.* (2014) identified the collective behavioral difference among soccer players (under-9, under-11 and under-13 years old) concerning tactics during games. It was concluded that younger teams tend to have a higher length and a lower width relation in their pitch position. This suggests that younger players have quick approaches to the goal by using the depth of the pitch (Ouellette, 2004). Game conditions also created differences within the same age group. This is of particular importance when designing training sessions tailor made for each player. Games therefore can help understand the tactical implications. With video technology used to monitor player movement in this study (Folgado, 2014) a recommendation for future studies would be the implementation of GPS technology to examine PlayerLoad values recorded across age groups in relation to tactical awareness. A study by Sampaio and Maçãs (2012) discusses the tactical behaviour in soccer through the use of 5Hz portable GPS units. One of the main strategic decisions in football is team positioning and distribution on the playing pitch (Kannekens, Elferink-Gemser and Visscher,

2010). Most of the posterior tactical behaviour is conditioned by player coordination and respect to team formation. Global Positioning System technology is becoming very common to describe activity profiles according to players' specific positions (Aughey, 2010; Gray and Jenkins, 2010; Wisbey et al., 2010). Positioning is strategically and tactically conditioned therefore it is relevant to monitor players via GPS to analyse repetitive patterns during dynamic movement. Sampaio and Maçãs (2012) calculated the mean position of all 5 players on one team (x, y) in order to produce the geometric centre of the team. The distance of each player from the centre was recorded at speeds below and above $13 \text{ km} \cdot \text{h}^{-1}$. This study is the first of its time in the area of movement patterns under such conditions since previous literature has focused on physiological requirements by using distance covered, speeds and accelerations, disregarding positional data (Coutts et al., 2010; Gray and Jenkins, 2010; Wisbey et al., 2010). Decision-making forms the basis of players' movement patterns. It was found that players' movement was more conditioned to their teammates positioning than by the pitch location. Looking at the coordinates separately the results showed that the players had a higher improvement in length displacement (y coordinate) meaning that players are more focused on moving forwards and backwards along the pitch, as opposed to moving across (x coordinate) the pitch. The variables used in this study suggest that the farthest players to the geometric centre (probably forwards) have to be skilled in direct build-up of play, and be the first line of the defensive process to regain possession (Bangsbo and Peitersen, 2000). Therefore, the results suggest that the players' movement is more intentional and thus increased their participation in defensive and offensive game phases. In contrast to the forwards, the closest players to the geometric circle were midfielders. This position has a major role of communicating between defenders and forwards through carrying and passing the ball (Bangsbo and Peitersen, 2000; Wade, 1997). This position is closer to the centre of the team and reflects the need to search for better passing lines and angles (Wade, 1997). Analysing

dynamic positional data during match play is a way of measuring tactical behaviour. One advancement in this field would be to incorporate measurements of PlayerLoad (ax, ay and az) in order to analyse whether specific positions have clear differences. Portable GPS units have been included in soccer training as a method of evaluating player performance. Training sessions include small-sided games with a combination of pitch dimensions and player numbers to manipulate tactical, technical and physiological demands (Casamichana and Castellano, 2010; Dellal et al., 2011a, Hill-Hass et al., 2008; Köklü, 2012; Little, 2009; Sampaio and Maças, 2012). The use of GPS technology to monitor athlete performance during small-sides games has typically examined distance covered and the subsequent distance recorded over various speeds. In the instances where PlayerLoad has been included (Aguiar et al., 2013; Casamichana et al., 2014; Castellano, Casamichana and Dellal, 2013) it is not clear whether more players or fewer players elicit greater load. Tri-axial accelerometry can be included in the biomechanical analysis of small-sided games. That way the understanding of the biomechanical profile in relation to age and playing position (that have shown to differ physically, tactically and technically) can increase.

2.3.2 Applications of GPS analyses during match play

Each elite level team in the Australian Football League (AFL) collects data during each competitive match for some or all of the players on the roster (Aughey, 2011b). Studies have shown that AF players cover between 113 and 152 m·min⁻¹ during games (Aughey, 2011b; Wisbey et al., 2010). Matches can last up to 111 min, so these figures can be translated to ≈ 17 km per game with 5.1 km (or 30% of the distance) covered at high-intensity or high-speed running (Aughey, 2010; Coutts et al., 2010). Comparatively, soccer players record ≈ 107 m·min⁻¹ during games and total distance of ≈ 11 km (Barnes et al., 2014; Russell et al., 2014; Terje et al., 2016). In addition to match play, GPS has been used during training sessions

in order to monitor intensity (Aughey, 2011a). Match data in AFL has been used in order to try and develop training drills that have been previously discussed. One study concluded that a club's training sessions produced a decrease of high-velocity and high-intensity activities that ranged from 18% to 60% in comparison to matches (Boyd and Ball, 2008). Analysis of training has also included PlayerLoad through accelerometer data (Boyd et al., 2010; Boyd, Ball and Aughey 2011). Through this research, training drills have been categorised based on PlayerLoad. In reference to matches the latter study found a strong relationship between total distance and PlayerLoad ($r=0.90$). These two variables have been found to have a large correlation ($r=0.70, p<0.01$) in soccer small-sided games (Casamichana and Castellano, 2015; Casamichana et al., 2013). The reported correlation is derived from the calculation of PlayerLoad (Boyd, Ball and Aughey, 2011) where load only accumulates with a change in acceleration. Small-sided games record multidirectional movements, sprints and frequent accelerations as a result of pitch dimensions and number of players (Aguiar et al., 2013; Casamichana et al., 2014; Dellal et al., 2011a). The constant bouts of acceleration and deceleration phases therefore result in accumulation of high PlayerLoad values. Training drills that are conducted with larger pitch dimensions may not require such movement patterns and would result in a decrease in PlayerLoad. The decrease in PlayerLoad, due to running at constant speeds for example on a large pitch without constant change of direction and accelerations may also affect the correlation between PlayerLoad and total distance, typically found with small-sided games.

PlayerLoad has also been measured in rugby union; an intermittent high-intensity sport with activities requiring maximal power and periods of lower intensity aerobic activity and rest (Nicholas, 1997). Cunniffe *et al.* (2009) conducted a study examining the physical demands of elite rugby union. This study used GPS technology (SPI Elite; GPSports Systems, Canberra, Australian Capital Territory, Australia) and underlined the challenges faced when analysing

rugby union with video footage or via notational analysis due to the dynamic gait changes over the course of a game. Global Positioning System data were recorded at 1Hz and accelerometry (tri-axis) data at 100Hz. Over the course of a game backs recorded a PlayerLoad value of 376 AU (393 AU 1st half, 344 AU 2nd half) and forwards had a PlayerLoad value of 1426 AU (843 AU 1st half, 1833 AU 2nd half). This difference in values is attributed to playing positions and the number of impacts received due to the nature and rules of the sport. With positional differences evident in PlayerLoad values and activity profile, the current thesis will examine the biomechanical profile of soccer players in relation to both performance and loading metrics (Barnes et al., 2014; Russell et al., 2014; Terje et al., 2016). The analysis conducted in this study can be applied to training sessions (i.e. replication of game demands), conditioning and evaluation of overall game stress (Cunniffe et al., 2009).

A review article compiled by Gray and Jenkins (2010), underlined the applications of GPS technology in Australian Football (AFL) as a tool for match analysis (distance, speed) and physiological response (heart rate) measurement. Gray and Jenkins (2010) did not include PlayerLoad as a match analysis parameter. Global Positioning System technology is providing coaches with objective and detailed data concerning specific movement demands of players based on their position. After changes in speed have been recorded, position specific training programmes can be developed and PlayerLoad can be monitored both during competition and training. This in turn can lead to the analysis of PlayerLoad in relation to overuse injuries (Gray and Jenkins, 2010). As found in the previous section of this literature review, match analysis has not been afforded biomechanical positional profiling. As match running performance fluctuates (Coutts et al., 2010) during match play the inclusion of PlayerLoad examination could provide a mechanical profile of the sport.

In contrast to the vast amount of research conducted in AFL, soccer is starting to be examined with reference to player monitoring through GPS units. The physiological demands of soccer

have been presented (Di Salvo et al., 2007), therefore it would be useful to discuss the findings of studies conducted with elite youth soccer players. Harley *et al.* (2010), used 112 elite youth male soccer players (11-16 years) that represented the under 12 (U12), under 13 (U13), under 14 (U14), under 15 (U15) and under 16 (U16) teams. These players represented two English professional clubs and data was analysed from 14 competitive matches with the use of 5Hz Portable GPS units (MinimaxX, Catapult Innovations, Canberra, ACT, Australia). Six speed zones (standing $<1 \text{ m}\cdot\text{s}^{-1}$; walking $<2 \text{ m}\cdot\text{s}^{-1}$; jogging $<3 \text{ m}\cdot\text{s}^{-1}$; running $<4 \text{ m}\cdot\text{s}^{-1}$; high-speed running $<5 \text{ m}\cdot\text{s}^{-1}$; sprinting $\geq 6 \text{ m}\cdot\text{s}^{-1}$) were set for each age group by their mean flying 10 metre sprint times. The U15 and U16 group were faster ($1.35 \pm .009 \text{ s}$; $1.31 \pm 0.06 \text{ s}$) than the U12 ($1.58 \pm 0.10 \text{ s}$, U13 ($1.52 \pm 0.07 \text{ s}$) and U14 ($1.51 \pm 0.08 \text{ s}$) age groups. Absolute total distance was significantly higher at U16 level ($7672 \pm 2578 \text{ m}$) than at U12 ($5697 \pm 1277 \text{ m}$), U13 ($5812 \pm 1160 \text{ m}$) and U14 ($5715 \pm 2060 \text{ m}$) levels. High-intensity distance followed the same trend with the U16 level covering $2481 \pm 1044 \text{ m}$ compared to U12 ($1713 \pm 371 \text{ m}$), U13 ($1756 \pm 520 \text{ m}$), U14 ($1841 \pm 628 \text{ m}$) and U15 ($1755 \pm 591 \text{ m}$) levels. Overall, in absolute terms (m) the U16 age-group displayed higher absolute total distance (U16 > U12, U13, U14), high-intensity distance (HID; U16 > U12, U13, U14), very high-intensity distance (VHID; U16 > U12, U13) than the other four age-groups. When analysing the findings relative to match exposure (minutes played) the U14 level accumulated a significantly higher VHID compared to the U13 level (14.3 and $11.1 \text{ m}\cdot\text{min}^{-1}$ respectively). Overall speed zones in relation to match exposure for all age groups were distributed as follows: HID 9.2% (5 – 14%), VHID 3.1% (1 – 5%) and sprinting 1.01% (0 – 2%). It must be noted that these numbers are a result of the different game durations among the age groups and in relation to total match distance the figures are significantly different (30.4%; 11.9%; 3.6%). These figures are a result of the significantly positive correlations between match exposure and total distance ($r^2=0.736$; $p<0.001$) HID ($r^2=0.542$; $p<0.001$) VHID ($r^2=0.378$; $p<0.001$) and sprint distance ($r^2=0.236$;

$p < 0.001$). In addition, match play ranged from 13 to 97 minutes for the players. Since the U16 level had the highest match exposure (71 ± 26.4 min) the significantly higher absolute values may be a result of this. This study correctly noted that speed thresholds should be 'normalised' based on individual or group capabilities. The data collected during match play showed that players become significantly faster between the U14 and U15 age groups alluding to training drills that should replicate match demands (Harley et al., 2010). The study by Harley *et al.* (2010) examined elite youth football across various ages and applied GPS applications to distance and speed without consideration of other variables. This research project will examine various ages and positions on the basis of distance, speed and PlayerLoad in an attempt to provide a more representative profile of the physical and biomechanical demands of soccer. Portable GPS units have been used during matches in team sports to provide an indication of the demands imposed on the players. Where PlayerLoad was reported during matches (Cunniffe et al., 2009) tri-axial accelerometry does not provide the distribution of contributing accelerations (ax, ay, az). Discovering the acceleration distribution would provide more precise information of the movement profile of players. Positional and age differences exist based on the distance and speed data provided by previous research (Aughey, 2011b; Aughey, 2010; Coutts et al., 2010; Harley et al., 2010; Wisbey et al., 2010). This observation of an altered activity profile with playing age will intuitively have implications for the biomechanical response to match play. In this respect the application of GPS analyses can be extended beyond the performance metrics associated with distance and velocity profiling. The integrated use of incorporated technologies such as tri-axial accelerometry broaden the potential scope of player profiling to include biomechanical markers.

2.3.3 Applications in Tri-Axial Accelerometry

The formula used to calculate PlayerLoad (Catapult Innovations, Australia) was presented by Boyd, Ball and Aughey (2011).

$$\text{PlayerLoad} = \sqrt{\frac{((a_{y_{t=i+1}} - a_{y_{t=i}})^2 + (a_{x_{t=i+1}} - a_{x_{t=i}})^2 + (a_{z_{t=i+1}} - a_{z_{t=i}})^2)}{100}}$$

This is based on the change in acceleration in the antero-posterior (ax) medio-lateral (ay) and vertical (az) planes. The tri-axial PlayerLoad formula has been applied to studies in team sports (Casamichana et al., 2015; Coad, Gray and McLellan, 2016; McLaren et al., 2016; Sparks, Coetzee and Gabbett, 2016; Vickery, Dascombe and Duffield, 2016;). The limitations of applying this formula include summation of accelerations that masks the directional profile (medio-lateral or antero-posterior or vertical) and application of the square and then square root to data that negates orientation of acceleration (medial or lateral, anterior or posterior, take-off or landing).

More recently GPSports adopted an alternate parameter that they refer to as New Body Load.

$$\text{New Body Load} = \sqrt{(a_y^2 + a_x^2 + a_z^2)}$$

This equation represents a fundamental difference from PlayerLoad in the processing of the raw acceleration data, with PlayerLoad utilising the change in acceleration, whereas New Body Load utilises the magnitude of acceleration. This would naturally provide very different values, limiting comparison between systems in what is designed to be an equivalent parameter. This raises concerns regarding the validity of the loading metrics used in previous GPS analyses (Ehrmann et al. 2016; Lovell et al., 2013; Sullivan et al., 2014).

Time motion analysis systems are capable of measuring activities that are quantified by distance and speed data collected (Bangsbo, Mohr and Krstrup, 2006; Bradley et al., 2010; Di

Salvo et al. 2007; Gregson et al., 2010; Montgomery, Pyne and Minahan, 2010; Rampinini et al., 2009). With soccer being a highly-intermittent sport it is important for time motion analysis systems to quantify typical soccer movements like kicking, passing and tackling in addition to the more mechanically demanding sprinting, accelerations and decelerations. Terje *et al.* (2016) monitored elite soccer players over the course of three seasons and categorised them according to playing position. Player movement was assessed through RadioEye™ (ZXY SportTracking AS, radionor Communications AS, Norway) a fully automatic sport tracking system. The accelerometers used to measure Player load had a sampling frequency of 20Hz. Equation for Player load is found below as sum of high-passed filtered data:

$$(X, Y, \text{ and } Z): ((X^2) + (Y^2) + (Z^2)) / 800$$

X: mediolateral axis; Y: anteroposterior axis; Z: vertical axis

The match data presented higher Player load for central defenders, central midfielders, wide midfielders, and attackers, than full backs. Central midfielders had a greater Player load than attacker (9%). There was a 5% decrement in Player load across all playing position between the 45-minute periods of the matches. With reference to distance covered players covered on average 10200 ± 785 m for low intensity activities during match play. Full-backs and wide midfielders covered greater high-intensity distance than central defenders (>230%), central midfielders (>48%), and attackers (>40%), respectively. Analysing physical and biomechanical variables variables can provide an in depth player profile based on playing position. The implications of the variety of Player load values collected for each playing position can be addressed through specificity of training in order for effective adaptation to match requirements (Terje et al., 2016).

Recently, Bowen *et al.* (2016) considered total load (total of the forces on the player over the entire session based on accelerometer data alone) in relation to injury incidence.

$$\text{Total Load} = \sqrt{((aca_{t=i+1} - aca_{t=i})^2 + (acl_{t=i+1} - acl_{t=i})^2 + (acv_{t=i+1} - acv_{t=i})^2)}$$

where *aca* is acceleration along the anterior–posterior axis, *acl* is acceleration along the lateral axis and *acv* is acceleration along the vertical axis, *i* is current time and *t* is time. This is then scaled by 1000 (StatSports, Ireland).

Elite level youth soccer players were monitored during training sessions and matches through the use of portable 10Hz GPS units (Viber V.2, StatSports, Ireland). Specifically, high weekly total load (474-648 AU) recorded the greatest significant relative risk for overall (RR=1.65, 95% CI 1.04 to 2.62, *p*=0.032) and non-contact injuries (RR=2.20, 95% CI 1.25 to 3.9 *p*=0.007). Very high weekly total load (<648 AU) significantly increased the incidence of contact injuries (RR=4.84, 95% CI 1.26 to 18.55, *p*=0.022). A low weekly total load (0-130 AU) significantly reduced overall (RR=0.27, 95% CI 0.12 to 0.60, *p*=0.002), and non-contact injury risk (RR=0.31, 95% CI 0.11 to 0.86, *p*=0.024). The findings by Bowen *et al.* (2016) could assist a sport scientist in devising the timeframe to introduce injury prevention exercises or relay the information to the coaching staff to protect players when alterations in PlayerLoad are evident. The epidemiology of soccer injury has been well described (Ekstrand, Hägglund and Waldén, 2011a, 2011b; Hägglund, Waldén and Ekstrand 2013; Hawkins et al., 2001; Junge and Dvorak, 2013; Woods et al., 2003, 2004), with most injuries occurring in the lower limbs, and comprising muscular strain or joint sprain. The mechanism of injury is consistently reported as being non-contact (Junge and Dvorak, 2013; Woods et al., 2003, 2004), with running, and particularly changing direction the most common mechanism (Ekstrand, Hägglund and Waldén, 2011a; Woods et al., 2003, 2004). Given the importance of multi-directional running in the activity profile of football (Ali, Spendiff and Brouner, 2016;

Bloomfield, Polman and O'Donoghue, 2007; Dellal et al., 2010a), the activity profile can itself be considered an inherent risk factor for injury. The application of GPS analysis could therefore be extended beyond performance metrics to include more biomechanically specific parameters. In addition to a consistent reporting of injury type and mechanism in soccer, the aetiology of injury consistently highlights fatigue as a risk factor (Ekstrand, Hägglund and Waldén, 2011a; Hawkins and Fuller, 1999). More injuries are observed to occur during the latter stages of match play (Ekstrand, Hägglund and Waldén, 2011a; Hawkins and Fuller, 1999). This temporal pattern mirrors observations of impaired performance during match play.

Monitoring movement patterns during matches could provide feedback to sport scientists in order to devise injury prevention strategies if an anomaly is recorded. Injury audits are a method of properly addressing the types of risks players experience over the course of a season. Fatigue affects high-intensity efforts during a game and laboratory-based studies have shown it affects cognition, decision-making, technical ability and skill (Kellis, Katis and Vrabas, 2006; McMorris and Graydon, 1997; Rampinini et al., 2008). These parameters then act as aetiological markers for injury. If movement is compromised, then injury risk increases. With such a large percentage of non-contact injuries in soccer and running cited as the most common mechanism (Woods et al., 2003), movement mechanics can be a contributing factor. Therefore, it is quite evident that in both hamstring and ankle injuries portable GPS units could prove an effective tool since they have the capacity of recording the movements that can increase risk of injury. That way it would provide a holistic view of a player's movement pattern and susceptibility to injury for the coaching and medical staff alike.

Providing the distribution of load across the frontal, sagittal and vertical planes is limited in soccer research. Barron *et al.* (2014), monitored tri-axial PlayerLoad during eight 11v11 competitive youth soccer matches with 5Hz portable GPS units with 100Hz accelerometers. Match data concluded that contribution for vertical, anteroposterior and mediolateral force

was ~ 44:29:26%. Greater detail in the uni-axial medio-lateral acceleration might be valuable in relation to joint sprain aetiology, and performance metrics when considering positional profiling. Recently, Brown and Greig (2016) reported tri-axial accelerometry data from an injury case study in Premier League football. The injured player sustained a lateral ankle sprain, and exhibited a clear asymmetry in medial:lateral acceleration in contrast to other squad players who completed the same session but did not sustain an injury.

Cormack *et al.* (2014) and Fish & Greig (2014) considered the influence of playing position on tri-axial loading in netball players. Centre players exhibited the greatest load, similar to that observed for midfield players in soccer. In accordance with Barron *et al.* (2014) the players accumulated a greater proportion of load in the vertical plane in comparison to antero-posterior and medio-lateral. Fish and Greig (2014) reported a ratio of 47:25:27 for vertical, antero-posterior and medio-lateral accelerations, which was not position-dependent. The relative contributions of medio-lateral and antero-posterior contributions between soccer and netball most likely reflects the restrictions placed on player movement in netball, and court dimensions. These restrictions might be considered in relation to the interventions used within small-sided games in soccer training, with evident implications for the biomechanical response. Cormack *et al.* (2014) reported that the dominant vertical loading contribution was in part explained by sprinting and accelerating/decelerating involving more rapid vertical displacement than slower speed running. Cormack *et al.* (2014) also identified that, with reference to periods of play, Shooters displayed a reduction of -16.4 ± 17.8 percent in load between the first and fourth quarters. It was inconclusive whether the reduced load was a result of lower running volumes across a range of intensities or other neuromuscular factors namely fatigue (Cormack *et al.*, 2014). Whilst soccer-specific applications are limited to date, these studies do highlight the potential of uni-axial analysis of movement profiles. Furthermore, the

lack of consensus in the calculation of a loading metric warrants further investigation, with fundamental biomechanical principles in place.

2.4. Validity and Reliability in GPS parameters

Kinetics and kinematics of team sport movements have customarily been measured in laboratories using force plates or multiple-camera analysis systems. Such a process, although internally valid and reliable, limit the understanding of movement workloads players experienced during training and match play (Crewther et al., 2010; Payton and Bartlett, 2007). Subjective workload monitoring techniques have also been developed such as RPE, however, these lack the validity and reliability of the laboratory setting (Borresen and Lambert, 2009). Therefore, it is difficult to obtain ecologically valid and reliable pitch-side measures of movement workloads using these techniques. Alternative techniques capable of measuring individual and team workloads during both training and match play are needed. Performance monitoring using accelerometers may be possible as acceleration is proportional to external force and may more accurately reflect the frequency and intensity of the movements performed (Yang and Hsu, 2010). Of note, the validity of GPS will be affected by sampling rate which has increased from 1Hz to 10Hz in the soccer literature, and thus direct comparison between studies requires caution (Duffield et al., 2010; Petersen et al., 2009). One aspect of assessing the suitability of GPS usage in soccer is examining its validity in comparison to other technology available for the monitoring of players. A common metric associated with GPS is velocity, based on the first differential of the coordinate-time history. Speed has previously been quantified using sprinting tasks measured through the use of infra-red timing gates over short intervals (Cronin and Templeton, 2008; Duthie et al., 2006). Waldron *et al.* (2011) compared timing gates (Brower Timing Systems, Draper, UT) and GPS units (GPSports, SPI-Pro, 5Hz, Canberra, Australia) in a study comprising elite youth male

rugby players who were assessed over two maximal sprint efforts. Validity was evaluated by comparing mean speed at 10m, 20m, and 30m between the two systems of measurement. The data showed significant differences ($p<0.05$) between timing gate and GPS values, although no values for effect size were reported to more clearly understand the practical significance of the data presented. Mean biases ranged from 2.01 km·h⁻¹ to 2.19 km·h⁻¹. Coefficient of variance (CV) over all speed variables ranges from 5.7% to 9.8%. The authors reported an underestimation of GPS measurements compared to measured distances and timing gate calculations of speed at all measured intervals, but better reliability in GPS. Timing gates provide an average velocity over the prescribed distance, rather than the instantaneous velocity provided by GPS data and thus direct comparison is limited. Timing gates are also influenced by the height of the unit, such that a forward swing arm might trigger data capture whilst the centre of mass is behind this free swinging limb. This issue is negated when using GPS, and thus the potential for continuous monitoring of speed during exercise is a primary advantage. Global Positioning System technology has been compared to subjective notational analysis (Dogramaci, Watsford and Murphy, 2011) and semi-automated video match analysis recognition systems (e.g. Harley et al., 2011). Dogramaci, Watsford and Murphy (2011) quantified six locomotor activities (walking 0 m·s⁻¹, jogging 3 m·s⁻¹, running 5 m·s⁻¹, sprinting 7 m·s⁻¹, sideways/backwards 3 m·s⁻¹) during the completion of futsal-specific activities on an outdoor court. Movement was analysed via portable GPS units (GPSports Systems, Canberra, Australia) and a camera (Panasonic, Osaka, Japan). The researchers suggested sprinting values were similar for GPS (5 ± 6.5 m) and notational analysis (7 ± 7.8 m). However, raw (m) values were significantly different for jogging (68.6 ± 18.9 m; 187.1 ± 16.7 , $p<0.01$) and total distance ($1,101.9 \pm 52.6$ m; $1,265.4 \pm 64.5$, $p<0.01$). The notational analysis of all the other activities has shown it to be methodologically sound for monitoring player movement. It is worth noting that the monitoring took place in an outdoor court however with futsal games frequently taking

place in indoor facilities notational analysis would be adopted as GPS would be unable to track distance, duration and frequency of activities (Dogramaci, Watsford and Murphy, 2011). Recently however, Catapult (Catapult Innovations) has developed ClearSky that uses portable satellites for athlete monitoring in indoor facilities. The tri-axial accelerometry function will work indoors, and furthermore GPS can provide additional analysis with the embedded collection of heart rate data and can track more than one participant in contrast to notational analysis (Carling et al., 2008).

Global Positioning System technology has also been compared to semi-automated video match analysis recognition systems, namely Prozone[®]. Harley *et al.* (2011), fitted six elite level soccer players with 5Hz GPS units (MinimaxX, Catapult) while their movement was quantified using Prozone[®]. The variables included in this study were total distance (TD), high speed running distance (HSR; $4\text{--}5.5\text{ m}\cdot\text{s}^{-1}$), very high speed running distance (VHSR; $5.5\text{--}7\text{ m}\cdot\text{s}^{-1}$), sprint distance (SPR; $>7\text{ m}\cdot\text{s}^{-1}$), high-intensity running distance (HIR). There were significant differences ($p<0.05$) in TD (Prozone[®] $1613.3 \pm 239.5\text{m}$, GPS $1755.4 \pm 245.4\text{m}$, $p=0.31$, ES=0.51, 95% CI= 0.05-0.97), SPR (Prozone[®] $34.1 \pm 24\text{m}$, GPS $20.3 \pm 15.8\text{m}$, $p=0.019$, ES=0.68, 95% CI= 0.12-1.2) and HIR (Prozone[®] $368.1 \pm 129.8\text{m}$, GPS $317 \pm 92.5\text{m}$, $p=0.034$, ES=0.45, 95% CI=0.04-0.86). These differences can be attributed to the calculation of distance (and the next differential in velocity) in each of the systems, and would limit an intuitive model of using GPS in training and Prozone[®] for matches to monitor weekly intensity. For a sport scientist, these findings help in understanding the relationship of reported data between the two systems when analysing external player work-load (Harley et al., 2011). With recent changes enabling the collection of GPS data during matches, with the consent of the governing body, there is less need to try to embed different technologies.

Measuring differences in data among GPS manufacturers offers valuable information on precision of performance indicators. Randers *et al.* (2010) examined the variation in reading of

two GPS units (GPS1: MinimaxX v 2.0, Catapult, Scoresby, Australia, and GPS2: GPSports, SPI Elite, Canberra, Australia). The two units generated data from at least three satellites and were set at a time resolution of 5 and 1Hz respectively. The study design consisted of a test soccer match (two 47.5 min halves with a 15 min interval in between) with 20 highly trained outfield soccer players (19.3 ± 1.2 years, 73.6 ± 5.3 kg, 1.79 ± 0.06 m). The results of the study showed that GPS1 tended to record longer distance (17%) for high intensity running (2 ± 0.76 km) than GPS2 (1.67 ± 0.48 km, $p=0.07$). The two GPS units recorded the following distances for low-intensity running (GPS1: 3.04 ± 0.65 km; GPS2: 2.98 ± 0.66 km), and total running distance (GPS1: 5.04 ± 1.34 km; GPS2: 4.88 ± 1 km). There was no significant difference ($0.008 < p < 0.05$) in sprinting summations (GPS1: 0.36 ± 0.23 km; GPS2: 0.22 ± 0.16 km). The only variable with a significant difference ($p < 0.001$) was total distance covered (GPS1: 10.76 ± 0.80 km; GPS2: 9.64 ± 0.03 km). It must be noted however, that walking contributes one-third to one-half of total distance covered during a game. The significant difference recorded for this variable is not of immediate biomechanical interest since this speed of movement does not create the large amount of physical loading that is present at higher velocities during match play (Randers et al., 2010). The high intensity distance recorded by the MinimaxX unit (2.03 km) is consistent with the literature (Di Salvo et al. 2007; Mohr, Krstrup and Bangsbo, 2003). The difference in this value for the SPI Elite unit may be a result of the sampling frequency of 1Hz since the MinimaxX unit is set at 5Hz. Consequently, GPS2 measured only about 50-75% of the number of sprints detected by GPS1 (15.1 ± 8.9 vs 28.2 ± 9.6). This is an indication that such time-resolution is not sufficient to measure high-speed activities. Sprints in soccer tend to occur at very high intensities over short distances, usually less than 20 m, therefore, since 1Hz GPS units have impaired accuracy over shorter distances they may not accurately report sprint distance (Scott, Scott and Kelly, 2016). Higher GPS sampling frequency is desirable to quantify actions at higher speeds and validity of GPS units depends on the parameters being measured.

Speed and distance metrics can provide information for player profiling purposes when examining the demands of soccer. Such metrics can also be analysed with relation to biomechanical variables. The relationship between indicators of training load is indicative to the performance demands of football. Casamichana *et al.* (2013) analysed the correlation of PlayerLoad to variables of training load. The 44 monitored training sessions recorded a large correlation ($r=0.70$, $p<0.01$) between PlayerLoad (PL) and Total Distance (TD). Without overlooking the importance of acceleration, it must be noted that the correlation reported in the study (Casamichana *et al.*, 2013) is derived from the calculation of PlayerLoad (Boyd, Ball and Aughey, 2011) that suggests PlayerLoad only accumulates with a change in acceleration. Total distance covered at constant speed will result in a low value of PlayerLoad since there will be high vertical load but lower medio-lateral and antero-posterior load. In training sessions PlayerLoad records correlations to total distance (Casamichana and Castellano, 2015; Casamichana *et al.*, 2013) due to the nature of movement in drills such as small-sided games. With the manipulation of pitch dimensions of a small-sided game players accumulate high PlayerLoad due to constant bouts of acceleration and deceleration phases. With the PlayerLoad formula (Boyd, Ball and Aughey, 2011) based on changes in acceleration, sprinting will result in higher values of this biomechanical variable. Training drills with larger pitch dimensions may not require such constant bouts of acceleration and deceleration phases and would decrease PlayerLoad. This decrease may also affect the relationship between PlayerLoad and total distance that has been recorded during drills with smaller pitch dimensions. This can help explain a correlation of $r=0.70$, which equates to 49% of the variance in load being accounted for by change in distance covered (Casamichana *et al.*, 2013). The number of directional and/or speed changes will also influence PlayerLoad, and whilst inherent in soccer-specific activities the frequency and magnitude of changes in acceleration will be a more mechanistic predictor of PlayerLoad than distance covered.

When utilising GPS technology it is important to consider the capabilities of the system for example in real-time (RT) mode as opposed to post-game (PG). The units allow data to be collected as athletes participate in matches in addition to processing the data through the software after them. Therefore, it is helpful to know if there are any differences present when deciding to collect data. Aughey and Falloon (2009) examined real-time versus post-game GPS data in Australian Football. Since team performance and strategy can change through the course of a game it is important to examine whether the data generated in real-time is a valid indicator of physical effort that has been determined by previous games. Twelve elite athletes participated in the study and wore GPS units (MinimaxX, Catapult Innovations) for two games during the 2008 season. Data on running was collected based on custom speed zones; jog 4.2-5, run 5-6.9, sprint 6.9-10 $\text{m}\cdot\text{s}^{-1}$. The results for RT and PG were as follows, jog 367 ± 144 and 440 ± 198 , run 488 ± 193 and 450 ± 194 , sprint 121 ± 110 and 98 ± 105 . Total distance covered was 3378 ± 702 and 3223 ± 798 respectively. The range of error between both data sets makes it quite difficult to make decisions based on player performance during a match. In the case of Australian Football, many coaches use RT data to support rotating decisions as a mode of fatigue regulation. Of particular interest to sport scientists is that the largest error occurs at higher speed running. The discrepancy of measures may be a result of differing algorithms used when calculating distance in speed zones. Therefore, with caution required when using RT data to monitor performance it may be preferred to rely on PG data in order to make valid conclusions in reference to the variables measured (Aughey and Falloon 2009). This thesis utilised post game GPS data for analysis of player performance.

A variable embedded in the portable GPS units analysed in this thesis is PlayerLoad (instantaneous and accumulated rate of change of acceleration in three planes of movement) (Boyd, Ball and Aughey, 2011). Tri-axial accelerometers are highly sophisticated motion sensors that measure the frequency, magnitude and orientation of body movement in three

planes (Boyd, Ball and Aughey, 2013). The accuracy and reliability of this technology is high, providing measures that can objectively be assessed (Varley, Fairweather and Aughey, 2012). Higher sampling rate (10Hz compared to 5Hz) rate demonstrated improved reliability during constant velocity and acceleration and deceleration phase (coefficient of variation <5.3% and <6% respectively). In addition, 10Hz GPS can detect the smallest change during constant velocity and acceleration phase for 1-3 m s⁻¹ and during the deceleration phase. Similar findings were recorded during the constant velocity and acceleration phase for 3-5 m s⁻¹ and 5-8 m s⁻¹ (Varley, Fairweather and Aughey, 2012). From research conducted to date, the most valid and reliable devices are the 10Hz GPS units, the optimal GPS tracking device in team sports (Scott, Scott and Kelly, 2016).

2.5 Summary

Presently GPS technology has been used in team sports as a mode of measuring the physical demands of the game in relation to the activity profile in order to prescribe training loads and intensities. The variable that has been used as an indicator of the aforementioned conditions has been total distance and movement at different bands of speed during small-sided games (Aguiar et al., 2013; Casamichana and Castellano, 2010; Dellal et al., 2011a). However, there are certain features of the technology that have not been used to their full potential. PlayerLoad is an example of one such a feature that can provide additional insight into the mechanical demands of the game. This variable is obtained via accelerometry combining the accelerations produced in three planes of body movement by means of a 100Hz tri-axial accelerometer (Boyd, Ball and Aughey, 2011; Cunniffe et al., 2009; Montgomery, Pyne and Minahan, 2010). This high sampling frequency is in contrast to the 1-10Hz sampling rate of the GPS unit, and appropriate for the characteristic intermittent and multidirectional profile involving rapid and nonlinear accelerations and decelerations. Consequently, PlayerLoad can quantify this

momentary variation in force accumulation making acceleration monitoring an area of interest for future research. This research project will address the need for the inclusion of biomechanical response in validating the demands of training drills, not solely on small-sided games that has been afforded a large body of research (Aguiar et al., 2013; Casamichana and Castellano, 2010; Gaudino, Alberti and Iaia, 2014; Mara, Thompson and Pumpa, 2016; Owen et al., 2012; Silva et al., 2014) with reference to distance and speed metrics. The application of this biomechanical analysis during match play will help better understand the influence of playing position on the physical response of match play. Research of soccer match play has provided insight on distances and speeds of various playing positions and ages (Barnes et al., 2014; Harley et al., 2010;) without the inclusion of PlayerLoad. In the research where PlayerLoad has been included during match play or training in soccer (Aguiar et al., 2013; Bowen et al., 2016; Casamichana and Castellano, 2015; Casamichana et al., 2014; Russell et al., 2015; Terje et al., 2016) a summation of tri-axial accelerometry was used and this does not provide the distribution of contributing accelerations (ax, ay, az). This research project will present the acceleration distribution across ages and positions providing more precise information of the movement profile of soccer players. Therefore, the further potential of tri-axial accelerometry with the inclusion of the contribution of each acceleration vector can provide a high frequency (100Hz) multi-parameter analysis of movement and such analysis has not been carried out to date.

Whilst the physiological demands of soccer have been well determined, the mechanical demands are less clearly defined. It is likely that the mechanical demands of the running profile will be position-dependent and that tri-axial accelerometry might provide a means for refined training prescription. For example, fatigue as a known factor in injury and performance, might be investigated using this application in order to provide coaching staff with information on players' readiness to train and compete. Features of the tri-axial accelerometry might provide

data on movement quality as opposed to gross measures such as distance covered and frequency of activities.

Chapter 3. The specificity of training drills to match play

3.1 Introduction

The physiological and biomechanical demands imposed on soccer players are a result of the intermittent and multi-directional activity profile of soccer, (Coutinho et al., 2015). Buchheit *et al.* (2014) and Carling (2013) suggest a valid physical response can be gained from soccer-specific drills. Small-sided games are used during soccer training sessions to develop technical and tactical (Almeida, Ferrera and Volossovitch, 2013) awareness whilst also developing physical conditioning as they appear to replicate requirements of competitive match play (Hill-Haas et al., 2008; Köklü, 2012; Little, 2009). The intended adaptations from a small-sided game are determined by various factors including duration (Dellal et al., 2008; Fanchini et al., 2011; Hill-Haas et al., 2010), number of drill repetitions (Fanchini et al., 2011), pitch area (Silva et al., 2014), number of players (Aguilar et al., 2013; Castellano, Casamichana and Dellal, 2013), and rules (Casamichana *et al.*, 2014; Castellano, Casamichana and Dellal, 2013; Mallo and Navarro, 2008).

Modifications of pitch area, number of players and rules (i.e. goalkeeper, number of goals scored) elicit different physiological responses (Impellizzeri et al., 2006). Whilst small-sided games in team sports are widely supported to develop sport specific aerobic fitness in youths and adults (Della et al., 2011a; Hill-Haas et al., 2010), the cognitive benefits of such games have also been well considered. Coaches implement practice drills followed by small-sided games with young athletes to promote the simple-to-complex principles of information processing (Davids et al., 2013). This practice places an emphasis on exploratory learning, considered to be a prerequisite for young athletes in acquiring skill (Chow et al., 2007). However, the relative lack of skill in young athletes places the positive outcomes of small-sided games under question (Vänttinen, Blomqvist and Häkkinen, 2010). Coaches might

therefore use less technical small-sided games to take advantage of the physiological benefits and increase acquisition of perceptual and decision-making making skills (Berry, Abernethy and Côté, 2008). Small-sided games postulate a cognitive rather than physical benefit, suggesting that physical adaptation intended by implementing such training drills is not to be taken for granted (Davids et al., 2013).

The mechanical response to small-sided games has received less consideration, arguably due to limited methodological opportunities prior to the development of GPS technologies. The physiological validity of small-sided games was summarised recently by Aguiar *et al.* (2013), advocating games with fewer players to increase physiological stress and larger games to address match-specific demands (Aguiar et al., 2013). This summary lends itself to a consideration of the mechanical demands of these games, as larger pitch dimensions will inevitably influence the running profile. With the development of GPS technologies, recent studies have included PlayerLoad in their evaluation of small-sided games. Castellano, Casamichana and Dellal (2013) reported that PlayerLoad was highest for 5 vs 5 games, whereas distance covered was greatest in 7 vs 7 games. The increase in distance covered is most likely a reflection on the increased pitch size for the 7 vs 7 game, but the disparity with greater PlayerLoad incurred during the smaller game was not clarified. Aguiar *et al.* (2013) showed the opposite relationship, with more players (4 vs 4) eliciting a greater load, whilst fewer players (3 vs 3) elicited the greatest distance covered. Casamichana *et al.* (2014) also quantified PlayerLoad in a comparison of 'free play' and conditioned 'two touch' small sided games of 6 vs 6, but failed to correlate this parameter with other measures of physical response.

The relatively contemporary development of such analysis limits the direct comparison of studies to date. With so many variables (duration, repetition, pitch dimension, player numbers, game conditions, etc.) open to manipulation by the coach, there are an infinite number of possibilities. To date, the studies using GPS to quantify the physical demands of training drills

have typically failed to relate the demands of these drills to the physical response observed during match play (González-Rodenas, Calabuig and Aranda, 2015; Joo, Hwang-Bo and Jee, 2016; Torres-Ronda et al., 2015). Furthermore, this emerging body of work has, to date, focused on senior players (Casamichana et al., 2014; Dellal et al., 2011a; Owen et al., 2011). Monitoring training and match performance is a fundamental role of the sports scientist in contemporary, elite youth soccer (Jones et al., 2015). The aim of the present study is to evaluate the physical demands of training drills implemented at a Premier League academy in relation to the demands of match play. The training drills as used by the coaches are categorised (according to their prescribed objective) as possession drills, movement pattern drills, game-related drills and small-sided games. This study therefore considers a more comprehensive battery of conditioned games than previously addressed in the literature, and a direct comparison with match play.

Research in soccer training has been aimed at analysing small-sided games through the manipulation of duration (Dellal et al., 2008; Fanchini et al., 2011; Hill-Haas et al., 2010), number of drill repetitions (Fanchini et al., 2011), pitch area (Silva et al., 2014), number of players (Aguiar et al., 2013; Castellano, Casamichana and Dellal, 2013), and rules (Casamichana *et al.*, 2014; Castellano, Casamichana and Dellal, 2013; Mallo and Navarro, 2008). Rather than considering the impact of a specific manipulation, the current study comprises the full suite of small sided games (n=96) used at an elite level football club academy. With no research design specified by intervention, the training drills are instead classified according to the performance objective as defined by the football club. The knowledge gained from the analyses of a comprehensive suite of training drills will help provide the anticipated practical utility for coaches to devise training sessions that replicate match demands.

3.2 Methodology

Participants

Thirty male outfield soccer players from an English FA Premier League club academy (age: 17.1 ± 0.7 years; height 176 ± 4 cm; mass 73.4 ± 5.9 kg) were monitored during training sessions ($n=20$) with twenty-two of the outfield players of the same team (17.8 ± 0.9 years; height 175 ± 5 cm; mass 75 ± 6.1 kg) monitored during 90-min competitive matches ($n=14$) over the course of one season (2011-2012). Institutional ethical approval was gained from Edge Hill University, through the Graduate School. Furthermore, player consent and approval by the football club was obtained during this study. The data arose as a condition of employment in which player performance was routinely measured over the course of the competitive season (Winter and Maughan, 2009). All match performance-related data were anonymised before analysis to ensure team and player confidentiality.

Procedures

Training sessions had a duration of approximately 90 minutes and comprised a 15 minute warm-up followed by drills that were categorised in the following groups; 'Possession Games' (players maintaining possession of ball through various passing sequences against players who try and block passes), 'Movement Pattern' drills (players maintain position and team formation while attacking and defending), 'Game-Related' drills (replicate game situations including player overloads, passing, receiving, finishing and crossing), and 'Small-Sided Games' (See Appendix 1). In this study 14 drills from each category were analysed ($n=96$). With reference to the 90-min competitive matches, only players completing the full match were included in the study.

External training load, that is training and match duration, distance traveled, running speed, and accelerations was monitored via GPS technology. Portable 10Hz GPS tracking devices

(MinimaxX S4, Catapult Innovations, Canberra, ACT, Australia) were worn during training sessions and competitive matches, placed between the shoulder blades in a custom-made undergarment. Physical performance measurements in this study include total distance covered (m), average speed ($\text{m}\cdot\text{min}^{-1}$), high-speed distance (distance $> 5.5 \text{ m}\cdot\text{s}^{-1}$), number of category 5 entries ($5.5\text{-}7.0 \text{ m}\cdot\text{s}^{-1}$), number of category 6 entries ($7.0\text{-}11.0 \text{ m}\cdot\text{s}^{-1}$) and PlayerLoad (instantaneous and accumulated rate of change of acceleration in three planes of movement) (Boyd, Ball and Aughey, 2011). Tri-axial accelerometers are highly sophisticated motion sensors that measure the frequency, magnitude and orientation of body movement in three dimensions (Boyd, Ball and Aughey, 2013). The accuracy and reliability of this technology is high, providing measures that can objectively be assessed (Varley, Fairweather and Aughey, 2012). Higher sampling rate (10Hz compared to 5Hz) rate demonstrated improved reliability during constant velocity and acceleration phase and deceleration phase (coefficient of variation $<5.3\%$ and $<6\%$ respectively). In addition, 10Hz GPS can detect the smallest change during constant velocity and acceleration phase for $1\text{-}3 \text{ m}\cdot\text{s}^{-1}$ and during the deceleration phase. Similar findings were recorded during the constant velocity and acceleration phase for $3\text{-}5 \text{ m}\cdot\text{s}^{-1}$ and $5\text{-}8 \text{ m}\cdot\text{s}^{-1}$ (Varley, Fairweather and Aughey, 2012). With data uniformity valid conclusions could be achieved. To facilitate comparisons between session type, parameters were standardised for session duration, so reporting $\text{load}\cdot\text{min}^{-1}$ for example.

Statistical Procedures and Tests

In a large body of motion analysis studies simple inferential statistical testing is the method used to explore data sets from games analyses of physical performance (Abt and Lovell, 2009; Barros et al., 2007; Bloomfield, Polman and O'Donoghue, 2007; Bradley et al., 2009; Bradley et al., 2010; Castagna et al., 2009; Dupont et al., 2010; Mohr, Krstrup and Bangsbo, 2003;

Mohr et al., 2010; Orendurff et al., 2010; Rampinini et al., 2007b; Rampinini et al., 2009; Rey et al., 2010).

Data from all game analyses were extracted from Catapult Sprint software (version 5.0) and collated using Microsoft Excel. In the study descriptive statistics for all variables were calculated and reported as means and standard deviations (mean \pm SD). A repeated measures analysis of variance (ANOVA) was employed to investigate differences in mean scores across the different measures of physical performance in each session category (possession drill, movement pattern drill, game-related drill, small-sided game, 90-minute match). Measure of Cohen's d effect size and 95% confidence intervals were reported for the mean difference for pairwise comparisons. The relationship between PlayerLoad and total distance was assessed using the Pearson's correlation coefficient. Magnitude of correlation coefficients was considered as trivial ($r < 0.1$), small ($0.1 < r < 0.3$), moderate ($0.3 < r < 0.5$), large ($0.5 < r < 0.7$), very large ($0.7 < r < 0.9$), almost perfect ($r > 0.9$) or perfect ($r = 1$; Hopkins, 2002). All the statistical analyses were performed using SPSS 20 (IBM, 2013) for Mac OS (Apple Computer), with significance being set at $p \leq 0.05$.

3.3 Results

Figure 3.1 presents total PlayerLoad recorded during each session (standardised for session duration). The total accumulated body load during match play (9.7 ± 0.4 AU/min) was significantly higher than that attained during 'Possession' drills (7.9 ± 2.2 AU/min; $p=0.001$; ES=1.01; 95% CI 0.98-2.62), 'Movement Pattern' drills (7.6 ± 1.3 AU/min; $p<0.001$; ES=1.46; 95% CI 1.59-2.61) and 'Game Related' drills (6.7 ± 0.9 AU/min; $p<0.001$; ES=2.01; 95% CI 2.63-3.37). There was no significant main effect between 'Small-Sided Games' (8.9 ± 1.01) and 90-minute match play. 'Small-Sided Games' were significantly different to 'Possession' ($p=0.047$; ES=0.57; 95% CI -0.04-2.04), 'Movement Pattern' ($p=0.009$; ES=0.99; 95% CI

0.59-2.01) and ‘Game Related’ drills ($p<0.001$; ES=1.51; 95% CI 1.62-2.78). ‘Possession’ drills were significantly different to ‘Game Related’ drills ($p=0.013$; ES=0.71; 95% CI 0.18-2.22).

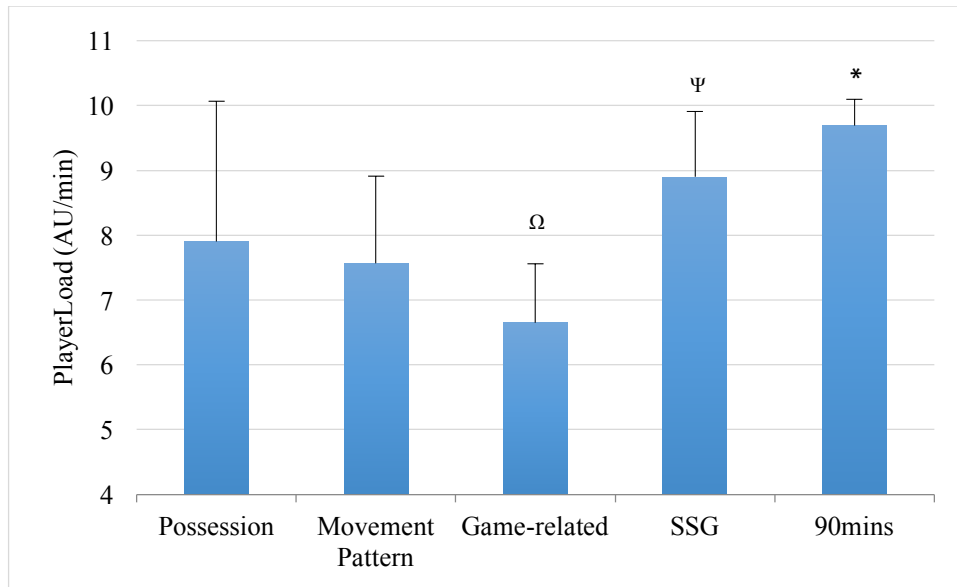


Figure 3.1. Total accumulated PlayerLoad (standardised for session duration) for training sessions and matches.

* significantly different ($p<0.01$) to possession, movement pattern and game-related.

Ψ significantly different to possession, movement pattern and game-related.

Ω significantly different to possession.

In Figure 3.2 the summary of total distance covered (standardised for session duration) during training drills and competitive matches is shown. Total distance during match play, ($104.5 \pm 5.1 \text{ m min}^{-1}$) was significantly higher than all training sessions. More specifically, ‘Small-Sided Games’ ($86.4 \pm 11.06 \text{ m min}^{-1}$; $p=0.001$, ES=1.46, 95% CI 13.50-22.70), ‘Game-Related’ drills ($65.3 \pm 13.6 \text{ m min}^{-1}$; $p<0.001$, ES=1.76, 95% CI 33.77-44.63), ‘Movement Pattern’ drills ($76.4 \pm 11.3 \text{ m min}^{-1}$; $p<0.001$, ES=1.69, 95% CI 23.43-32.77) and ‘Possession’ drills ($64.2 \pm 20.4 \text{ m min}^{-1}$; $p<0.001$, ES=1.61, 95% CI 32.53-48.07), were all significantly lower than that seen in match play.

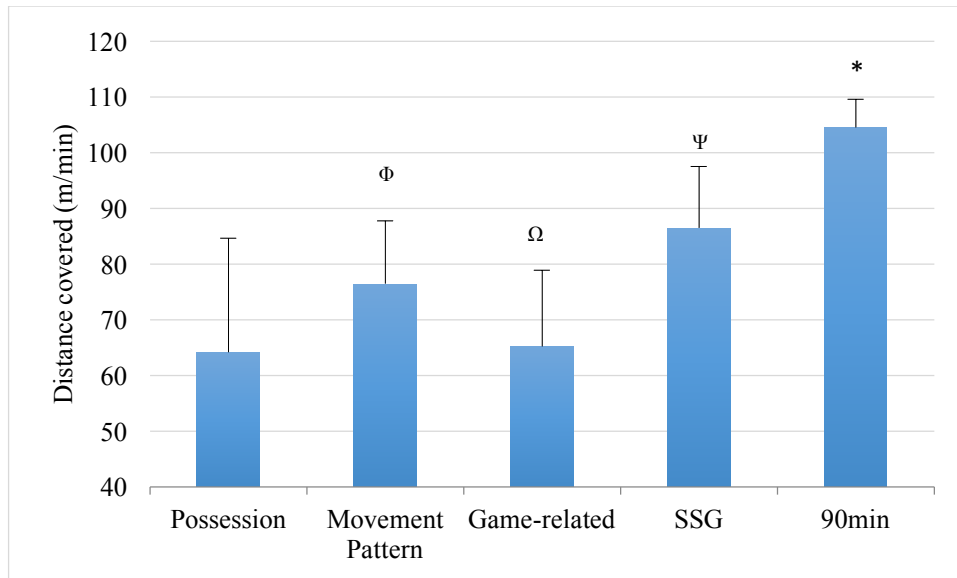


Figure 3.2. Total distance (standardised for session duration) for training sessions and matches.

* significantly different to all training sessions.

Ψ significantly different to possession and game-related.

Ω significantly different to movement pattern.

Φ significantly different to possession.

Table 3.1. summarises the correlation between PlayerLoad and total distance for each training session category and for competitive matches.

Table 3.1. Relationship between PlayerLoad and Total Distance.

Possession	Movement Pattern	Game-related	Small-sided Games	90-minute match play
$r=0.96,$ $p<0.001$	$r=0.68,$ $p=0.01$	$r=0.74,$ $p<0.001$	$r=0.92,$ $p<0.001$	$r=0.37,$ $p=0.19$

Figure 3.3 presents mean speed values (standardised for session duration) during training drills and competitive matches. Average speed during match play ($104.2 \pm 5.1 \text{ m} \cdot \text{min}^{-1}$) was significantly greater than all training sessions ($p<0.001$, “Small-Sided Games ES=1.55, 95% CI 13.82-21.78; ‘Possession’ ES=1.63, 95% CI 30.04-43.76; ‘Movement Pattern’ ES=1.68,

95% CI 22.90-32.50; ‘Game –Related’ ES=1.75, 95% CI 31.20-41.60). Average speed of ‘Small-Sided Games’ ($86.4 \pm 9.1 \text{ m}\cdot\text{min}^{-1}$) was significantly greater than ‘Possession’ drills ($67.3 \pm 17.8 \text{ m}\cdot\text{min}^{-1}$; $p<0.001$, ES=1.13, 95% CI 10.50-27.70), ‘Movement Pattern’ drills ($76.5 \pm 11.7 \text{ m}\cdot\text{min}^{-1}$; $p=0.034$, ES=0.87, 95% CI 3.52-16.28) and ‘Game-Related’ drills ($67.8 \pm 12.9 \text{ m}\cdot\text{min}^{-1}$; $p<0.001$, ES=1.28, 95% CI 11.81-25.39).

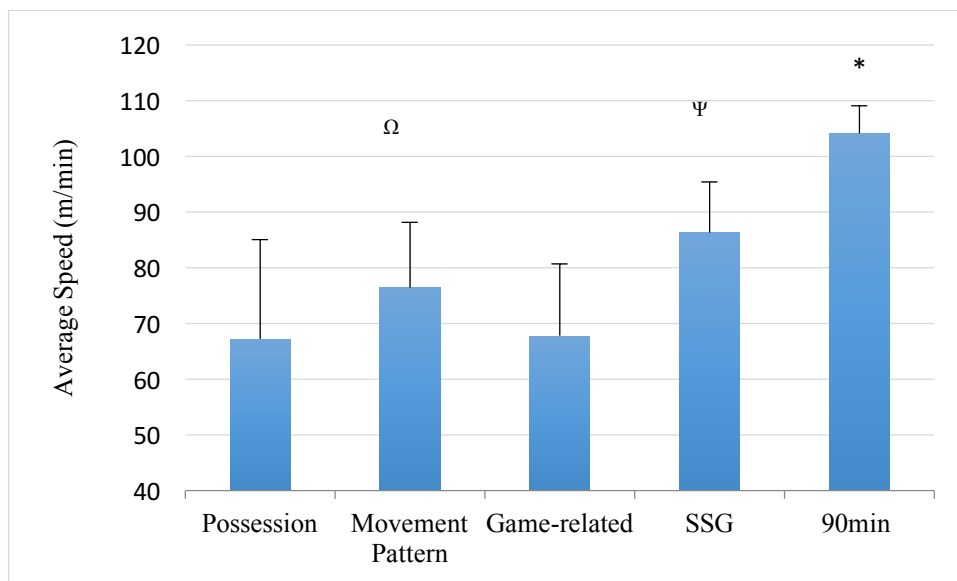


Figure 3.3. Average speed for training sessions and matches.

* significantly different to all training drills.

Ψ significantly different to all training drills and matches.

Ω significantly different to possession drills.

Comparisons between session type for (standardised duration) high-speed distance ($5.5\text{-}11 \text{ m}\cdot\text{s}^{-1}$) are shown in Figure 3.4. Match play high-speed distance ($5.10 \pm 1.32 \text{ m}\cdot\text{min}^{-1}$) was significantly greater than ‘Small-Sided Games’ ($0.63 \pm 0.52 \text{ m}\cdot\text{min}^{-1}$; $p<0.001$, ES=1.80, 95% CI 3.87-5.07), ‘Game-Related’ drills ($2.18 \pm 1.2 \text{ m}\cdot\text{min}^{-1}$; $p<0.001$, ES=1.51, 95% CI 2.20-3.64) and ‘Possession’ drills ($0.36 \pm 0.64 \text{ m}\cdot\text{min}^{-1}$; $p<0.001$, ES=2.12, 95% CI 4.13-5.35). ‘Small-Sided Games’ recorded significantly lower high-speed distance than ‘Game-Related’

drills ($p=0.008$, $ES=1.09$, 95% CI 0.99-2.11) and ‘Movement Pattern’ drills (4.17 ± 2.75 $m \cdot min^{-1}$; $p<0.001$, $ES=1.34$, 95% CI 2.34-4.74).

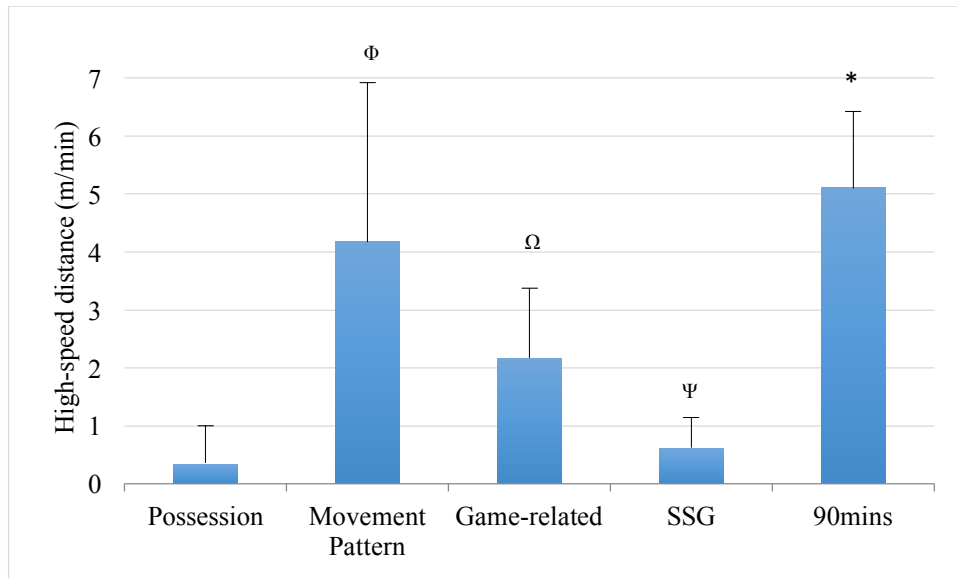


Figure 3.4. High-speed ($>5.5 m \cdot s^{-1}$) distance (standardised for session duration) for training sessions and matches.

* significantly different to possession, game-related and small-sided games.

Ψ significantly different to movement pattern and game-related.

Ω significantly different possession and movement pattern.

Φ significantly different to possession.

The differences in number of category five high-speed entries ($5.5-7.0 m \cdot s^{-1}$, standardised for session duration) are shown in Figure 3.5. Match play number of entries (0.27 ± 1.1 per min) were significantly greater than ‘Small-Sided Games’ (0.06 ± 0.52 per min, $p<0.001$, $ES=1.62$, 95% CI -0.30-0.72) and ‘Possession’ drills (0.02 ± 0.03 per min, $p<0.001$, $ES=1.67$, 95% CI -0.22-0.72). The number of entries for ‘Small-Sided Games’ were significantly lower than ‘Game-Related’ drills ($p=0.001$, $ES=1.37$, 95% CI -0.09-0.37) and ‘Movement Pattern’ drills ($p<0.001$, $ES=1.39$, 95% CI 0.01-0.49).

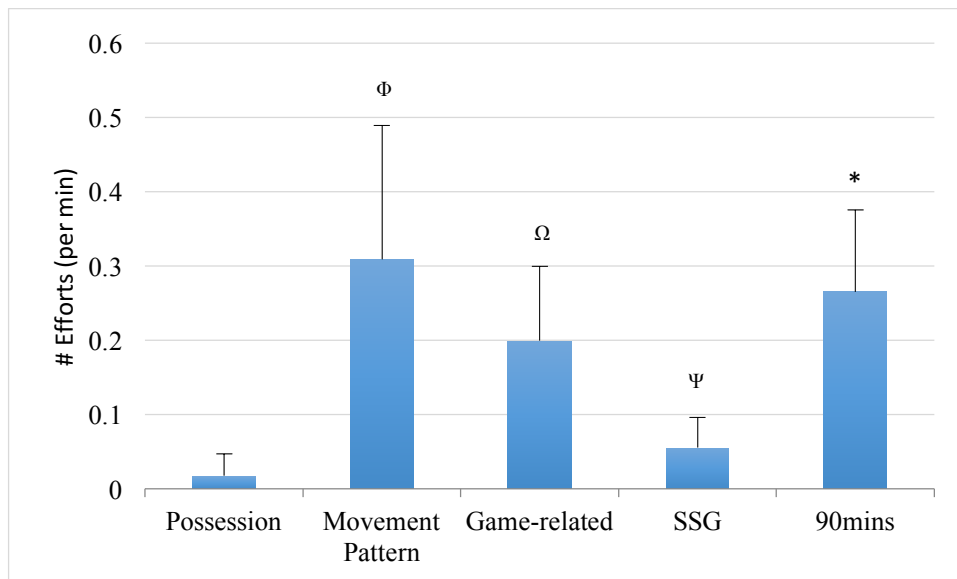


Figure 3.5. Number of category 5 ($5.5\text{--}7.0\text{ m s}^{-1}$) entries (standardised for session duration) for training sessions and matches.

*significantly different to possession and small-sided games.

Ψ significantly different to movement pattern and game-related.

Ω significantly different possession and movement pattern.

Φ significantly different to possession.

Figure 3.6 shows the influence of session type on the number of category six high-speed entries ($7.0\text{--}11.0\text{ m s}^{-1}$, standardised for session duration). Entries for Match play (0.07 ± 0.05 per min) were significantly greater than ‘Small-Sided Games’ (0.01 ± 0.02 per min; $p < 0.001$, ES=1.20, 95% CI 0.04-0.08), ‘Game-Related’ drills (0.01 ± 0.02 per min; $p < 0.001$, ES=1.20, 95% CI 0.04-0.08), ‘Movement Pattern’ drills (0.04 ± 0.04 per min; $p = 0.015$, ES=0.60, 95% CI 0.00-0.06) and ‘Possession’ drills (0.01 ± 0.02 per min; $p < 0.001$, ES=1.20, 95% CI 0.04-0.08). ‘Movement Pattern’ drills were significantly greater than ‘Possession’ drills ($p = 0.015$, ES=0.75, 95% CI, 95% CI 0.01-0.05), ‘Game-Related’ drills ($p = 0.020$, ES=1.00, 95% CI 0.01-0.05) and ‘Small-Sided Games’ ($p = 0.017$, ES=0.75, -5% CI 0.01-0.05).

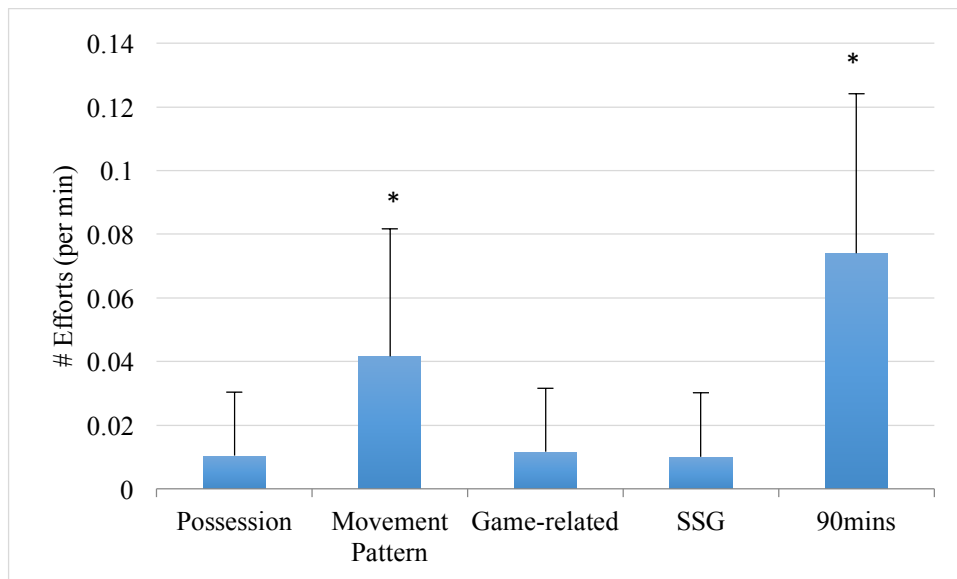


Figure 3.6. Number of category 6 ($7.0 - 11.0 \text{ m s}^{-1}$) entries (standardised for session duration) for training sessions and matches.

*significantly different to all variables.

To summarise the efficacy of each training session in replicating the demands of match play, Table 3.2 quantifies the percentage difference of each analysis variable relative to match play. In this Table a negative sign represents a value greater than that observed during match play, as shown for the number of Category 5 entries during Movement Pattern drills. In all other cases match play induced a greater demand. Each parameter is again standardised for session duration.

Table 3.2. Percentage difference of 90-minute match play data to training sessions.

	Player Load (AU)	Total distance	Average speed	High-speed distance ($>5.5 \text{ m s}^{-1}$)	Cat 5 Entries	Cat 6 Entries
Possession	18.6	38.6	35.4	92.9	93.0	98.6
Movement pattern	22.0	26.9	26.6	18.2	- 14.0	94.6
Game-related	31.4	37.6	35.0	57.3	25.9	98.6
Small-sided game	8.3	17.3	17.1	87.8	77.8	98.6

3.4 Discussion

The purpose of this study was to compare the physical demands of training sessions and competitive matches in elite youth soccer players, utilising a battery of analysis parameters currently employed by club staff. Training sessions did not record similar performance measures to competitive matches, with small-sided games having the smallest disparity to match data with reference to PlayerLoad and total distance (standardised for duration, and thus representative of average speed). However, those small sided games grossly under-represented the demands of high-speed running. Therefore, in this study, and contrary to previously reported research findings (Dellal et al., 2008; Fanchini et al., 2011; Hill-Haas et al., 2010; Hill-Hass et al., 2008; Köklü, 2012; Little, 2009), generally the training drills employed did not meet the requirements of match data.

Different drills displayed some measure of match play efficacy in specific analysis parameters. Whilst drills categorised as small-sided games were most closely related to match play in PlayerLoad and total distance covered, with discrepancies of 8.3% and 17.3% respectively, the discrepancy in high speed distance covered was 88%. This was also reflected in a 78-99% reduction in high speed zone entries. This observation might be attributed to the pitch dimensions being reduced so much that players were not given the space to acquire these high speeds. Previous research has shown that pitch dimensions will affect the physiological response to training drills (Aguiar et al., 2013; Casamichana et al., 2014; Impellizzeri et al., 2006; Mallo and Navarro, 2008), but here the reduced pitch size also has implications for the biomechanical demands. Distance and PlayerLoad are therefore accumulated at the lower speed zones with implications for physical conditioning. The generation of the higher speed running naturally requires a longer acceleration phase, and subsequently in deceleration (Maćkala, Fostiak and Kowalski, 2015). With a reduced pitch area this opportunity might be

removed. From a training specificity principle, these small-sided games have a clear biomechanical limitation therefore.

In contrast, the drills categorised as having an objective termed “movement pattern” were conducted on a greater pitch area. These drills elicited the best representation of match play with a deficit of 18% in high speed distance covered, and an increase of 14% in category 5 entries. Of note, no drill achieved a discrepancy less than 95% in the top speed zone entries. Thus pitch size, and providing space for players to acquire high speeds, will have an impact on the mechanical demands.

Studies examining small-sided games report data for the duration of a set of drills (Bradley et al., 2009; Casamichana and Castellano, 2010; Dellal et al., 2011a), whereas in this study data was standardised for session duration to allow direct comparison. In contrast to match play, the presence and interjection of coaching staff will influence performance, with continuous games eliciting greater distance than an intermittent format (Casamichana, Castellano and Dellal, 2013; Hill-Haas et al., 2009). Therefore, certain types of drills may elicit higher or lower demands based on their format and the way they are coached and/or conditioned.

The data collected for this study and subsequent analyses are a reflection of what drills are used in this particular club setting. With possession being the basis of competitive success many elite teams implement drills that improve this tactical concept of match play (Bradley et al., 2014; da Mota et al., 2016; Liu et al., 2015). It is important in this case for the intensity of such drills to replicate physical load players experience during competitive matches (Almeida et al., 2014). However, possession drills were carried out at a slow tempo in comparison to matches (67.26 ± 17.83 vs 104.19 ± 4.88 m·min⁻¹). This equates to 4.0 and 6.3 km·hr⁻¹ respectively. High-speed entries were virtually non-existent across the range of training drills analysed.

Research of small-sided games has focused on drills with standardised pitch dimensions, participants, and duration or altering one factor during studies (Aguiar et al., 2013;

Casamichana et al., 2014; Impellizzeri et al., 2006; Mallo and Navarro, 2008). The methodology allows for conclusions to be reached on the basis of how effective different small-sided games create the physical load of a match. This study looked at various combinations of small-sided games with reference to pitch dimensions and number of participants.

The use of PlayerLoad from the tri-axial accelerometry feature of the GPS technology is an additional marker of biomechanical intensity, with Casamichana and Castellano (2015) reporting a strong correlation between PlayerLoad and distance covered during small sided games. However, both Castellano *et al.* (2013) and Aguiar *et al.* (2013) reported a discrepancy between which small sided game format elicited the greatest Load, and the greatest distance covered. In the present study there was only a moderate correlation ($r=0.37$) between PlayerLoad and distance covered during match play. This would suggest that only 14% ($r^2=0.14$) of the variation in PlayerLoad is accounted for by changes in distance covered. In contrast, higher correlations were observed in movement patterns, game-related drills, small-sided games and possession drills in that hierarchical order. This relationship between PlayerLoad and distance is not intuitive when the calculation of PlayerLoad is considered. Load is accumulated when an acceleration takes place, and thus running at constant velocity in a straight line would accrue no increase in Load. As pitch dimensions get smaller, as observed in small-sided games and possession drills, the opportunity for constant velocity linear running is reduced. Here the movement pattern is likely to be characterised by a higher frequency of speed and directional change. In this case when the player moves and accrues distance, they are also likely to be changing direction and/or speed, both of which would accrue an increase in Load. Up to 90% of the variance in Load can be accounted for by changes in distance in possession drills for example.

This highlights another limitation in the use of PlayerLoad as calculated from tri-axial accelerometry, in that it is not clear in which movement plane the player has changed

acceleration (Boyd, Ball and Aughey, 2011). Changing direction would result in a change in Load even at constant velocity, since the directional change (for example from forward to sideways) would elicit a change in Load in both planes, with an increase in medio-lateral Load and a concurrent decrease in antero-posterior Load. Thus a high frequency of speed change or directional change, rather than necessarily a greater total distance covered, will elicit higher PlayerLoad values. This mechanistic evaluation of the calculation in PlayerLoad explains the difference in strength of correlation with distance based on the movement characteristics of each drill. This also highlights the limited use of tri-axial accelerometry when only considering total accumulated PlayerLoad with no consideration of the relative movement planes. The higher sampling frequency of the acceleration data at 100Hz in comparison to the 10Hz positional data used to derive distance covered is also a likely source of disparity.

The findings from this study clearly exhibit that the training failed to replicate the biomechanical demands of 90-min match play. With this premise, training in this manner will not provide players with the opportunity to optimally adapt to match requirements. In contrast to the widely accepted positive impact of exercise physiology in aiding player performance and training methods (Mohr, Krstrup and Bangsbo 2005), the potential of GPS-based tri-axial accelerometry to quantify PlayerLoad as biomechanical marker of exercise intensity remains under-utilised, (Barron et al., 2014; Cormack et al., 2013; Page et al., 2015). The tri-axial measurement of acceleration at 100Hz offers the same potential as force platform analysis, used widely in sports biomechanics in relation to both performance enhancement and injury prevention (Yeadon and Challis, 1994). Global Positioning System-based tri-axial accelerometry offers the potential to conduct high-frequency, multi-planar analyses of movement in a field setting. This potential greatly enhances the use of such technologies beyond the contemporary use of 10Hz GPS measures of distance covered. Through analysis of player movement during a 90-minute match a profile of mechanical load can be created on the

basis of playing position. Examining total PlayerLoad during a match will provide insight for sport scientists to create specialised training conditions that mirror the movement pattern recorded through GPS technology.

Presently, PlayerLoad is a value that indicates the changes in acceleration and this research project proposes to split movement into the three directions (ax, ay, az) in order to provide a complete profile of players' performance based on their position during match play.

Furthermore, the formula that is used for the GPS software provides a summation of the three forces.

$$\text{PlayerLoad} = \sqrt{\frac{((ay_{t=i+1} - ay_{t=i})^2 + (ax_{t=i+1} - ax_{t=i})^2 + (az_{t=i+1} - az_{t=i})^2)}{100}}$$

where

ay = acceleration in the antero-posterior (“forward”) plane

ax = acceleration in the medio-lateral (“side”) plane

az = acceleration in the vertical (“up”) plane

t = time

Tri-axial accelerometry offers greater scope for analysis in finer markers of movement quality.

At its simplest level, a player could score an equivalent value of PlayerLoad from a match, a vertical plyometric session, or a long constant-velocity run. Fundamentally each of these sessions are unique in their movement quality, but this is lost in the calculation of PlayerLoad.

The summation of directional vectors to a total value negates the relative contribution of each plane. Similarly, squaring the value in ay negates the opportunity to explore differential magnitude in anterior (forward) and posterior (backward) movement. This would be analogous to summing the tri-axial vectors in force platform analysis, to determine a ‘total’ ground reaction force, which is fundamentally flawed. Negating the difference between pronation and supination for example, and the relative magnitudes of tri-axial vectors would substantially reduce the potential of such analyses in sports biomechanics. Acceleration, as a vector quantity,

has both magnitude and direction. Calculations based on tri-axial accelerometry should therefore not negate either factor.

Since it is hypothesised that load on the body is proportionally different over the three planes it is important to be aware of the distribution of these forces. Thus, a simple arbitrary value does not allow for valid conclusions on PlayerLoad to be made. With a clearer method of calculating PlayerLoad decisions based on performance can be reached in a pre-habilitation manner. That is to say, coaching staff can make confident decisions on players' biomechanical condition and implement the relevant interventions.

3.5 Conclusion

Training sessions generally failed to match the mechanical demands of match play in an elite soccer academy. Whilst 'Small-Sided Games' provided the most valid demand in terms of distance covered and accumulated PlayerLoad, standardised for duration of the session, they failed to create a sufficient challenge in high-intensity running. This is likely to have implications for both mechanical and physiological development. Sessions described as 'Movement Pattern' drills were most effective in replicating the frequency and demands of high-speed running. The significant differences recorded between match play and all training drills with reference to distance covered and average speed pose a question to the effectiveness of such practice sessions. High-speed entries were virtually non-existent during training sessions. It could be concluded from the training drills analysed that players will not adapt to game requirements.

A secondary finding of this study was the relative lack of application in GPS-based applications. The data presented is that used by the football club, utilising a 10Hz positional coordinate data set to derive measures in distance and velocity. In contrast, the 100Hz and tri-axial nature of the accelerometry data used to calculate PlayerLoad is not well developed. The

lack of correlation between PlayerLoad and distance covered during match play highlights the mechanical foundations of the PlayerLoad calculation which depends only on changes in acceleration. This change in acceleration can be achieved by a change in speed or direction. As such the reduced playing area during small-sided games produced a stronger correlation between PlayerLoad and distance, since every change in locomotion is likely to be characterised as a change in direction and/or speed. As such the tri-axial nature of this device warrants greater attention and might provide greater detail in terms of movement quality.

CHAPTER 4. The influence of playing age on the physical response to soccer match play

4.1 Introduction

The use of GPS technology to measure distance covered, speed and acceleration in an objective manner (Cummins et al., 2013; Dwyer and Gabbett, 2012) has enhanced understanding of the physical demands of elite level soccer players (Buchheit et al., 2015; Buchheit and Mendez-Villanueva, 2013a, 2013b; Buchheit et al., 2012; Elferink-Gemser et al., 2012; Forbes et al., 2009; González-Badillio et al., 2015; Manna, Khanna and Chandra Dhara, 2010; Tomáš et al., 2014; Williams, Oliver and Faulkner, 2011; Wrigley et al., 2012;). Time motion analysis in elite level youth soccer has provided quantification of match performance across different age groups, but has typically failed to compare between age groups, and/or used a restrictive battery of physical measures (Buchheit, et al., 2010a, 2010b; Coutinho et al., 2015; Goto, Morris and Nevill, 2015; Harley et al., 2010; Mendez-Villanueva et al., 2013). In an elite football club academy, the objective is often to develop a ‘playing culture’, where the expectation is that a player can progress through the football club.

Harley *et al.* (2010) and Goto, Morris and Nevill (2015) quantified distance covered in elite U16 team players, but did not include PlayerLoad data or relate to other age groups. Buchheit *et al.* (2010a) compared elite U16 and U18 players, with a summary of the physical profile of each age group presented in Table 4.1. The similarity between the age groups is interpreted positively as preparing young players for the demands of competition as they progress. The primary difference in sprinting distance is likely to also have an influence on PlayerLoad which was not considered in the study.

Table 4.1. Physical profiles of elite soccer players (Buchheit et al., 2010a).

	Under 16 team	Under 18 team
Total distance (m)	8707 ± 1101	8867 ± 859
Low-intensity running (<13.0 km·h ⁻¹)	6749 ± 768	6650 ± 565
High-intensity running (13.1 – 16 km·h ⁻¹)	991 ± 370	976 ± 240
Very high-intensity running (16.1 – 19 km·h ⁻¹)	519 ± 155	574 ± 134
Sprinting distance 16.1 – 19 km·h ⁻¹)	449 ± 147	666 ± 256

If the objective of quantifying youth soccer is to establish its efficacy in developing physical preparedness for elite soccer, then analysis should be extended beyond youth soccer. In the present study, and within the remit of an elite football club academy, the U16 vs U18 comparison adopted by Buchheit *et al.* (2010a) is extended to include the U21 squad. This U21 squad is the oldest age-group specific squad before ‘senior’ soccer, and many of the U21 players would also be playing senior soccer. In extending the work of Buchheit et al. within an academy context, this is most likely the closest approximation of the transition into (and comparison with) senior football.

The present study also includes tri-axial measures of GPS-based accelerometry, as utilised in the previous chapter to examine the mechanical efficacy of small-sided games. The tri-axial nature of the accelerometry enables further analysis of the movement planes. Increased distance covered at high speeds is expected to increase PlayerLoad. Taking a force platform analogy, higher running speed would be associated with increased vertical and antero-posterior (A-P) forces, and thus accelerations. The multi-directional nature of the activity profile, not considered in the previous analyses of youth soccer, further complicate this mechanical complexity by increasing the medio-lateral (M-L) component of load. The present study will therefore quantify total PlayerLoad in each of the tri-axial movement planes.

Greater PlayerLoad in the medio-lateral plane would indicate, for example, greater lateral and/or cutting movements. Such detail in regards to movement quality can be used to further refine training practices, with specific relevance to the lack of validity observed in the previous Chapter in some training drills. Hence, the aim of this study was to analyse the physical and biomechanical profile of under-16 (U16), under-18 (U18) and under-21 (U21) elite level soccer teams.

4.2 Methodology

Participants

Players were recruited exclusively from the under-16 (U16), under-18 (U18) and under-21 (U21) teams of a Premier League soccer academy (same cohort as study one). In total, sixteen U16 (age: 15.3 ± 0.4 years; height: 168 ± 7.3 cm; body mass: 65.3 ± 8.3 kg), seventeen U18 (age: 17 ± 0.5 years; height: 176 ± 3.3 cm; body mass: 73.2 ± 5.3 kg), and seventeen U21 (age: 18.8 ± 0.6 years; height: 181 ± 9.2 cm; body mass: 79.3 ± 5.1) players were monitored for eight official games each ($n=24$) during the 2011-2012 season. Player consent and approval by the football club was obtained during this study which was noted by the University Research Ethics Committee (UREC). The data arose as a condition of employment in which player performance was routinely measured over the course of the competitive season (Winter and Maughan, 2009). All match performance-related data were anonymised before analysis to ensure team and player confidentiality.

Procedures

Match duration was 80 min for U16 soccer players, and 90 min for U18 and U21 players. Data from the U16 team were multiplied by 1.125 (90/80 match duration) in order to create findings equivalent to 90-minute match play of the U18 and U21 teams. Only players completing the

full match duration were included in this study. Portable 10Hz GPS tracking devices (MinimaxX S4, Catapult Innovations, Canberra, ACT, Australia) were worn for each game and were placed between shoulder blades in a custom-made undergarment. PlayerLoad (instantaneous and accumulated rate of change of acceleration in three force planes of movement) was derived from the tri-axial accelerometers at a frequency of 100Hz.

Distance covered (km) was analysed as a cumulative value for the whole game, and as the distance covered in each of four (pre-determined) speed zones (<2.0 , $2.0-4.0$, $4.0-5.5$, $5.5-7.0$ and >7.0 m.s⁻¹). Average speed (m.min⁻¹) was calculated for the entire match duration.

PlayerLoad (Boyd, Ball and Aughey, 2011) was also calculated as a cumulative total, and relative to each speed zone. PlayerLoad was calculated in each movement plane, and standardised for distance covered to enable comparisons between age groups. The ratio of each directional vector to total load was also calculated.

Statistical Procedures and Tests

Physical measures from all data sets ($n=154$) were extracted from Catapult Sprint software version 5.0 (Catapult Innovations, Canberra, ACT, Australia) and collated using Microsoft Excel. Descriptive statistics for all variables across three age groups were calculated and reported as means and standard deviations. A repeated measures analysis of variance (ANOVA) was employed to investigate differences in mean scores across the different measures of physical performance during the official matches. Measure of Cohen's d effect size and 95% confidence intervals were reported for the mean difference for pairwise comparisons. The relationship between PlayerLoad and total distance was assessed using the Pearson's correlation coefficient. Magnitude of correlation coefficients was considered as trivial ($r<0.1$), small ($0.1<r<0.3$), moderate ($0.3<r<0.5$), large ($0.5<r<0.7$), very large ($0.7<r<0.9$), almost perfect ($r>0.9$) or perfect ($r=1$; Hopkins, 2002). All the statistical analyses

were performed using SPSS 20 (IBM, 2013) for Mac OS (Apple Computer), with significance being set at $p \leq 0.05$.

4.3 Results

In Figure 4.1 the summary of total distance covered during competitive matches across U16, U18 and U21 teams is shown. Total distance covered during competitive matches was significantly greater for U16 team (10 ± 0.9 km) than U18 (9.2 ± 1 km, $p < 0.001$, ES 0.77, 95% CI=0.11-1.49) and U21 9.2 ± 1.3 km, $p < 0.001$, ES=0.69, 95% CI=0.04-1.62) teams. This pattern was evident in both halves, with the total distance covered during first and second period of competitive matches significantly greater for the U16 team (1st half 5.2 ± 0.6 km; 2nd half 4.9 ± 0.4 km) in comparison to U18 (1st 4.8 ± 0.6 km, ES=0.70, 95% CI=0.01-0.83; 2nd half 4.5 ± 0.5 km, ES=0.74, 95% CI= 0.04-0.70, $p < 0.001$ respectively) and U21 (1st half 4.7 ± 0.6 km, $p < 0.001$, ES=0.74, 95% CI=0.05-0.91; 2nd half 4.5 ± 0.7 km, $p < 0.004$, ES=0.55, 95% CI=-0.08-0.76) teams.

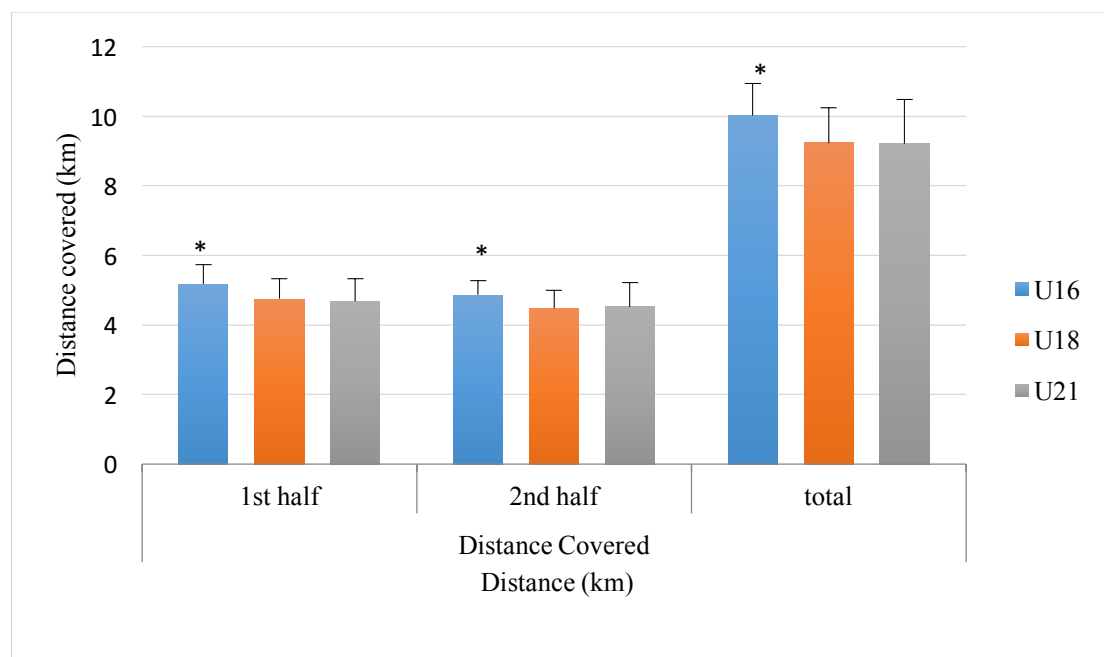


Figure 4.1. Total distance covered of U16, U18 and U21 teams.

*denotes significantly different ($p < 0.05$) to both teams.

Figure 4.2 is an overview of total distance covered during competitive matches across the five speed zones (<2.0, 2.0-4.0, 4.0-5.5, 5.5-7.0 and >7.0 m s⁻¹). Total distance covered at speed of 0-2 m s⁻¹ was statistically similar for U16 (3.8 ± 0.3 km), U18 (3.9 ± 0.5 km) and U21 teams (3.9 ± 0.3 km). Speed zone 2-4 m s⁻¹ revealed significantly greater distance covered for the U16 team (4.5 ± 0.9 km) in comparison to both U18 (3.9 ± 0.8 km, $p=0.001$, ES=0.69, 95% CI=0-1.2) and U21 teams (3.8 ± 1.1 km, $p<0.001$, ES=0.66, 95% CI=-0.02-1.42). The remaining three speed zones recorded non-significant differences among age groups. Specifically, during speed of 4-5.5 m s⁻¹ U16 (1.3 ± 0.3 km), U18 (1.1 ± 0.4 km) and U21 teams (1.1 ± 0.4 km) recorded similar values of distance. During speed of 5.5-7 m s⁻¹ U16 recorded similar distance (0.3 ± 0.1 km) to the U18 (0.3 ± 0.2 km) and U21 teams (0.3 ± 0.2 km). The highest speed zone 7-11 m s⁻¹ recorded the following distances, U16 (0.06 ± 0.09 km), U18 (0.09 ± 0.08 km) and U21 (0.08 ± 0.01 km).

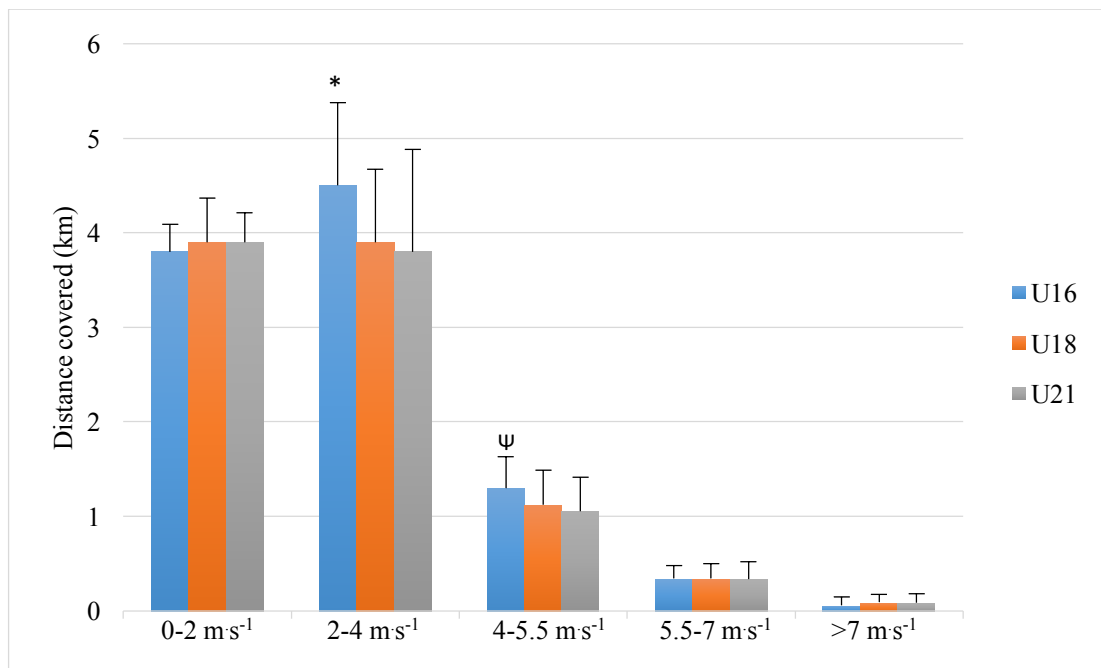


Figure 4.2. Distance covered of U16, U18 and U21 teams across five speed zones (<2.0, 2.0-4.0, 4.0-5.5, 5.5-7.0 and >7.0 m s⁻¹)

* denotes significantly different ($p<0.05$) to both teams.

Ψ denotes significantly different ($p<0.05$) to U21 team.

Figure 4.3 provides a summary of the contribution ratio of distance covered in each of the five speed zones (<2.0 , $2.0-4.0$, $4.0-5.5$, $5.5-7.0$ and >7.0 $\text{m}\cdot\text{s}^{-1}$) to total distance covered. U16 recorded a contribution ratio of 38:45:13:3:1 (± 5.7 , ± 5.2 , ± 2.6 , ± 1.5 , ± 1) for distance covered across five speed zones. U18 and U21 had contribution ratios of 42:41:12:4:1 (± 6.7 , ± 4.6 , ± 2.9 , ± 1.6 , ± 1) and 44:40:11:4:1 respectively (± 7.9 , ± 6.8 , ± 2.6 , ± 2 , ± 1.1). U16 recorded significantly less contribution to total distance over $0-2$ $\text{m}\cdot\text{s}^{-1}$ in comparison to U21 ($p<0.001$, $\text{ES}=0.8$, $95\% \text{ CI}=0.38-10.22$), however significantly greater contribution to total distance over $2-4$ $\text{m}\cdot\text{s}^{-1}$ than both U18 ($p=0.003$, $\text{ES}=0.76$, $95\% \text{ CI}=-0.08-6.88$) and U21 teams ($p<0.001$, $\text{ES}=0.77$, $95\% \text{ CI}=0.08-8.72$).

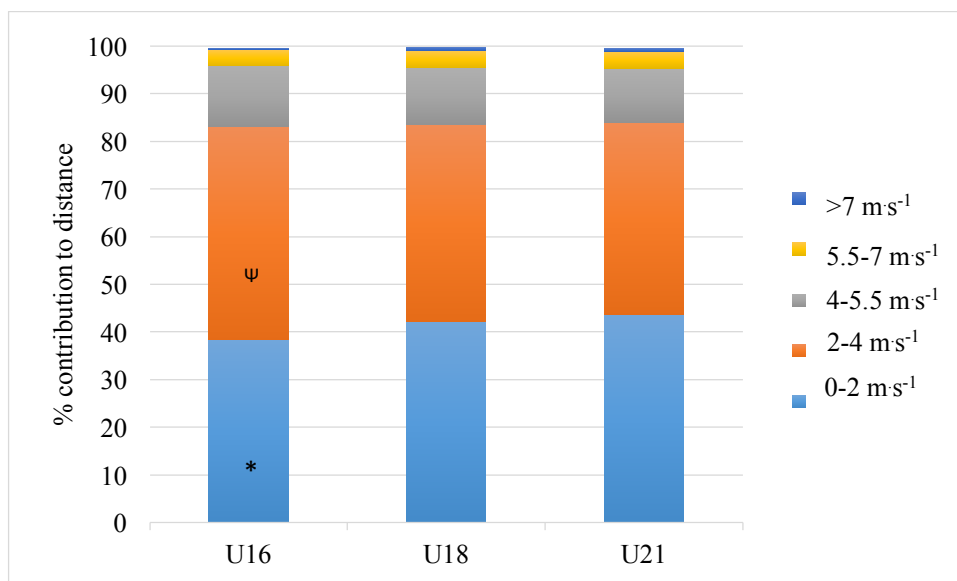


Figure 4.3. The speed zone contribution to distance covered of U16, U18 and U21 teams.

* denotes significantly different ($p<0.05$) to U21 team.

Ψ denotes significantly different ($p<0.05$) to both teams.

Average speed ($\text{m}\cdot\text{min}^{-1}$) during competitive matches for U16, U18 and U21 teams is presented in Figure 4.4. Average speed during U16 competitive matches ($108.7 \pm 9.8 \text{ m}\cdot\text{min}^{-1}$) was significantly higher than U18 ($100 \pm 11.2 \text{ m}\cdot\text{min}^{-1}$; $p<0.001$, ES=0.76, 95% CI=1.23-16.19) and U21 ($98.7 \pm 14 \text{ m}\cdot\text{min}^{-1}$; $p<0.001$, ES=0.75, 95% CI=1.31-18.61) teams.

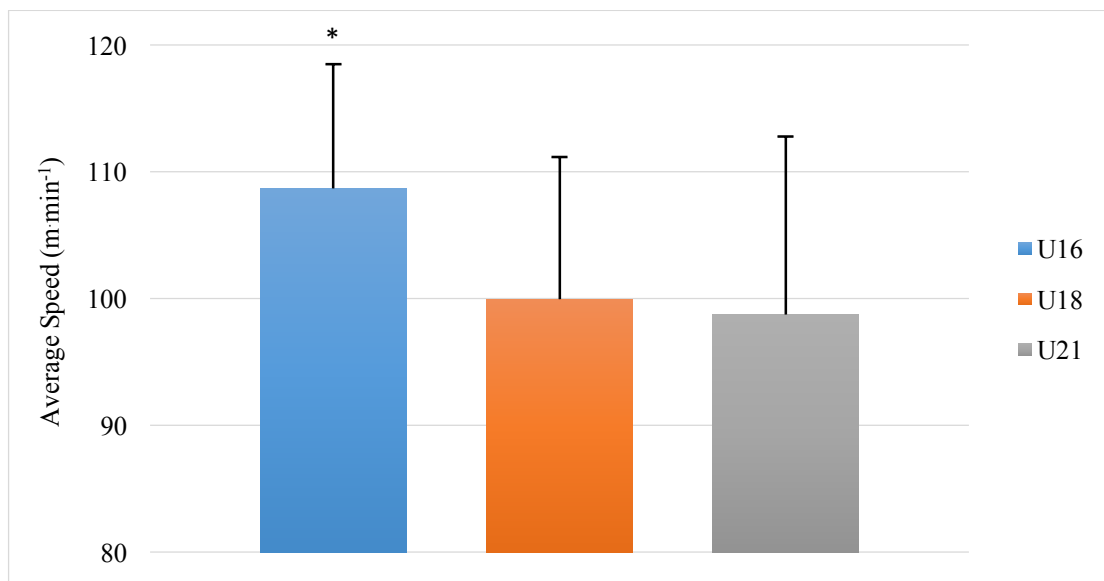


Figure 4.4. The average speed of U16, U18 and U21 teams.

* denotes significantly different ($p<0.05$) to both teams.

Figure 4.5 provides a summary of PlayerLoad across U16, U18 and U21 teams during competitive matches. PlayerLoad recorded during the first half for U18 competitive matches ($647 \pm 97.1 \text{ AU}$) was significantly greater than both U16 ($466.5 \pm 17.7 \text{ AU}$; $p<0.001$, ES=1.55, 95% CI=130.12-230.73) and U21 ($460.7 \pm 17.2 \text{ AU}$; $p<0.001$, ES=1.59, 95% CI=137.59-234.99) teams. During the second half PlayerLoad was significantly greater during U18 competitive matches ($606.5 \pm 83.4 \text{ AU}$) than both U16 ($455.1 \pm 16.9 \text{ AU}$; $p<0.001$, ES=1.54, 95% CI=108-194.70) and U21 ($453.8 \pm 19.3 \text{ AU}$; $p<0.001$, ES=1.56, 95% CI=110.43-194.97) teams.

teams. Total PlayerLoad during competitive matches was significantly greater for the U18 team (1253.5 ± 164.3 AU) in comparison to both U16 (921.7 ± 32.8 AU; $p<0.001$, ES=1.6, 95% CI=246.39-417.17) and U21 (914.5 ± 35.8 AU; $p<0.001$, ES=1.63, 95% CI=255.93-422.05).

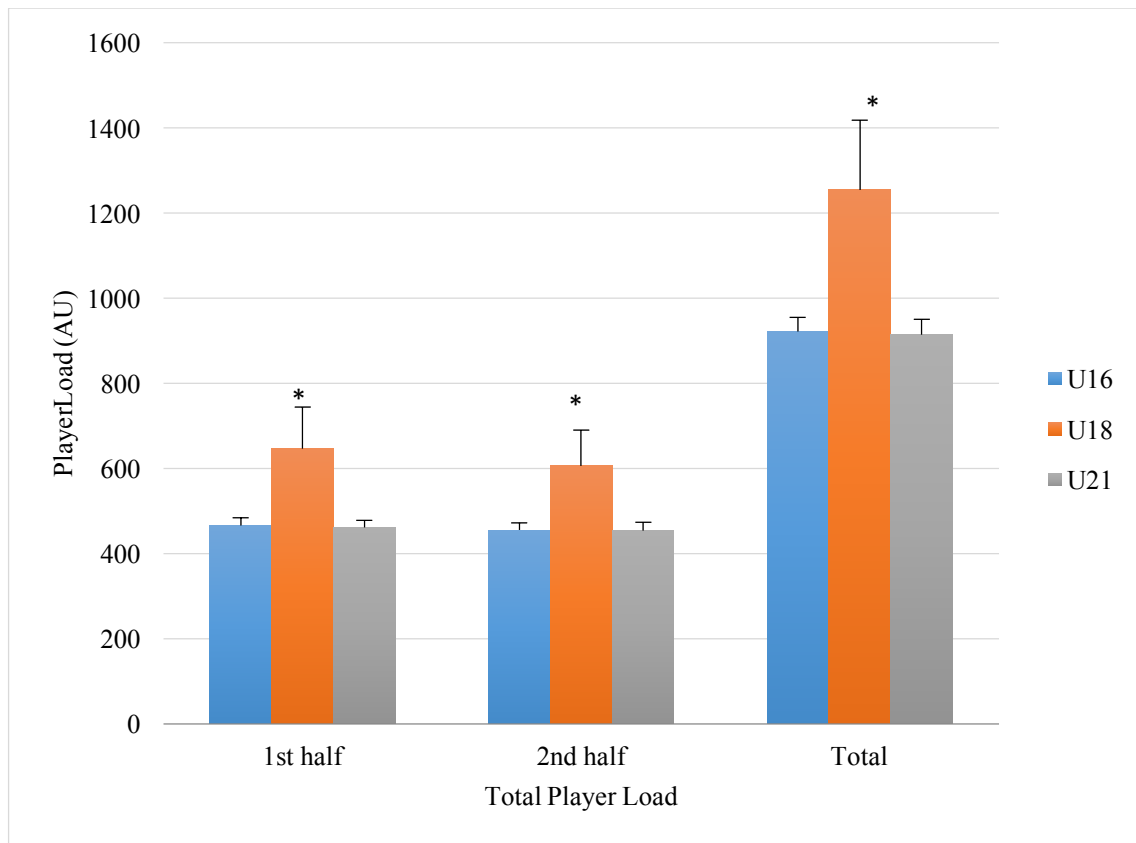


Figure 4.5. The Mean (\pm SD) PlayerLoad (AU) of U16, U18 and U21 teams.

* denotes significantly different ($p<0.05$) to both teams.

Uni-axial PlayerLoad recorded during competitive matches for U16, U18 and U21 teams respectively is presented in Figure 4.6. During first and second halves of competitive matches vertical load for the U18 team (1st half: 290.4 ± 47.1 AU; 2nd half: 268.1 ± 54.6 AU) was significantly greater than U16 (1st half: 241.9 ± 12.2 AU, ES=1.11, 95% CI=24.29-73.71; 2nd half: 238.1 ± 13.4 AU, $p<0.001$, ES=0.68, 95% C)=1.7-58.3) and U21 (1st half: 233.9 ± 14.6 AU, ES=1.25, 95% CI=32.7-81.1; 2nd half: 232.1 ± 15.5 AU, $p<0.001$, ES=0.82, 95% CI=8.3-63.7) teams. Anterio-posterior load during first and second halves of competitive matches for

the U18 team (1st half: 197.9 ± 45.9 AU; 2nd half: 186.2 ± 42.7 AU) was significantly greater than U16 (1st half: 151.9 ± 21.9 AU, ES=1.05, 95% CI=20.8-71.2; 2nd half: 148.2 ± 20.56 AU, $p<0.001$, ES=0.96, 95% CI=14.4-61.6) and U21 (1st half: 158.7 ± 23.8 AU, ES=0.94, 95% CI=14.1-63.8; 2nd half: 155.6 ± 24.8 AU, $p<0.001$, ES=0.80, 95% CI=7.1-54.9) teams. Medio-lateral load during first and second period of competitive matches for the U18 team (1st half: 158.6 ± 25.8 AU; 2nd half: 151.4 ± 22 AU) was significantly greater than U16 (1st half: 72.7 ± 9.2 AU, ES=1.62, 95% CI=72.5-99.5; 2nd half: 68.8 ± 8.6 AU, $p<0.001$, ES=1.72, 95% CI=71.1-94.9) and U21 (1st half: 68.1 ± 9.4 AU, ES=1.83, 95% CI=76.87-103.1; 2nd half: 66.1 ± 8.9 AU, $p<0.001$, ES=1.85, 95% CI=73.4-96.6) teams. Total PlayerLoad across the three planes recorded for the U18 team (az 558.5 ± 85.2 AU; ay 384.1 ± 86.7 AU; ax 310 ± 45.82 AU) was significantly greater than U16 (az 480 ± 25 AU, ES=1.03, 95% CI=32.9-123.1; fy 300.2 ± 42 AU, ES=1.02, 95% CI=35.5-132.6; ax 141.5 ± 17.4 AU, ES=1.69, 95% CI=144.6-193.5, $p<0.001$ respectively) and U21 (az 465.98 ± 29.75 AU, ES=1.17, 95% CI=48.6-137.4; ay 314.3 ± 48.3 AU, ES=0.89, 95% CI=21.3-118.7; ax 134.2 ± 18 AU, ES=1.85, 95% CI=152.1-199.9, $p<0.001$ respectively) teams.

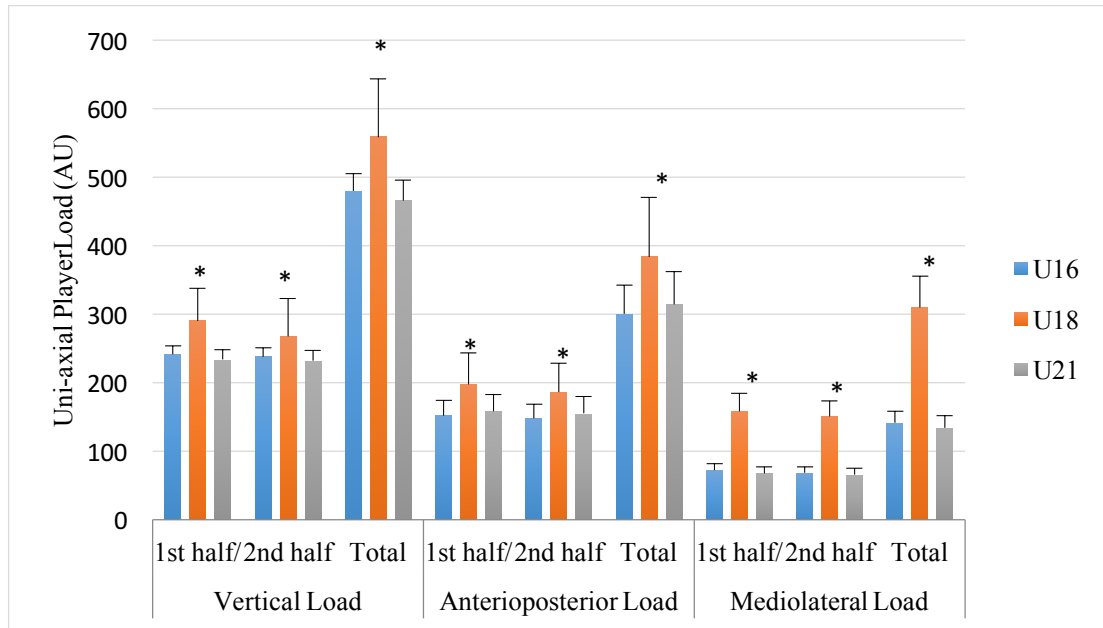


Figure 4.6. Uni-axial PlayerLoad (AU) of U16, U18 and U21 teams.

* denotes significantly different ($p < 0.05$) to both teams.

Figure 4.7 provides an overview of PlayerLoad percentage contribution ratio across medio-lateral, antero-posterior and vertical planes during competitive matches for U16, U18 and U21 teams. The PlayerLoad percentage contribution ratio for U18 team was significantly greater for medio-lateral load in comparison to U16 and U21 ($p < 0.001$, $ES = 1.87$, U18-U16 95% $CI = 8.10-10.70$, U18-U21 95% $CI = 8.80-11.38$ respectively) teams. Antero-posterior contribution ratio was significantly lower for U18 team in comparison to U16 ($p = 0.026$, $ES = 0.46$, 95% $CI = -1.00-4.94$) and U21 ($p < 0.001$, $ES = 0.77$, 95% $CI = 0.71-6.97$) teams. Significantly lower vertical load percentage contribution was recorded for U18 team in comparison to both U16 and U21 team ($p < 0.001$, $ES = 1.4$, 95% $CI = 4.76-10.24$, $ES = 1.21$, 95% $CI = 3.47-9.35$ respectively).

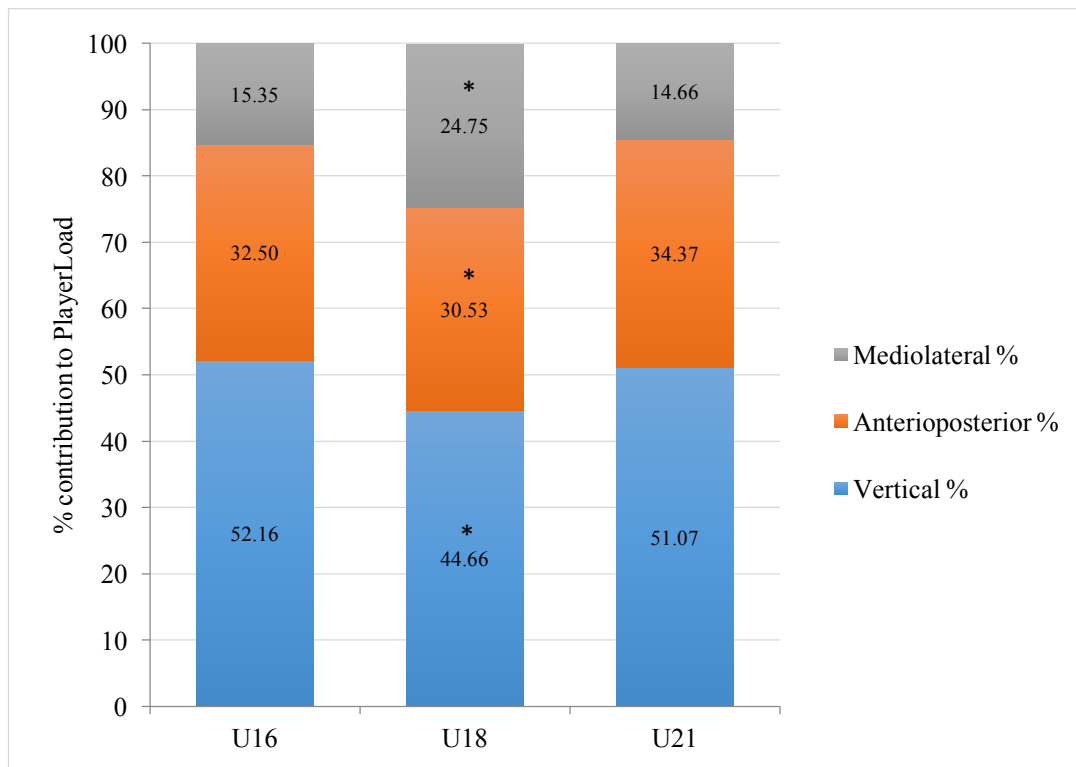


Figure 4.7. Uni-axial PlayerLoad contribution ratio of U16, U18 and U21 teams.

* denotes significantly different ($p<0.05$) to both teams.

Figure 4.8 provides a summary of PlayerLoad per distance covered during competitive matches for U16, U18 and U21 teams. PlayerLoad per distance covered for the U18 team (137.1 ± 22.7 AU/km) was significantly greater than both U16 (92.6 ± 7.9 AU/km, $p<0.001$, ES=1.57, 95% CI=32.28-56.72) and U21 (101.2 ± 14.1 AU/km, $p<0.001$, ES=0.69, 95% CI=22.67-49.07) teams. PlayerLoad per distance covered recorded for the U16 teams was significantly lower than the U21 team ($p=0.012$, ES=0.69, 95% CI=0.45-16.81).

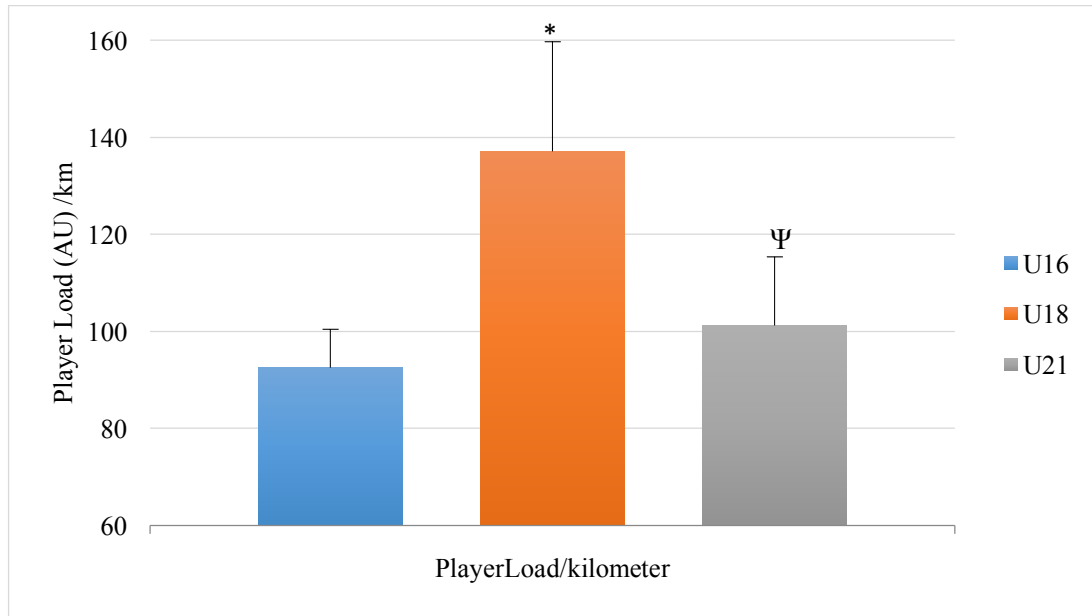


Figure 4.8. PlayerLoad per kilometer of U16, U18 and U21 teams.

* denotes significantly different ($p<0.05$) to both teams.

Ψ denotes significantly different to ($p<0.05$) to U18 team.

Table 4.2 provides a summary of the correlation between PlayerLoad and total distance for each 45-minute half of soccer match play across three age groups (U16, U18, U21).

Table 4.2. Relationship between PlayerLoad and Total distance.

U16		U18		U21	
1 st Half	2 nd Half	1 st Half	2 nd Half	1 st Half	2 nd Half
$r=0.56,$	$r=0.54,$	$r=0.32,$	$r=0.28,$	$r=0.26,$	$r=0.37,$
$p<0.001$	$p<0.001$	$p=0.02$	$p=0.04$	$p=0.06$	$p=0.01$

Table 4.3 quantifies PlayerLoad values across five speed zones (<2.0 , $2.0-4.0$, $4.0-5.5$, $5.5-7.0$ and >7.0 m s^{-1}) for the U16, U18 and U21 teams. In the first speed zone ($0-2$ m s^{-1}) the U18 team (325.5 ± 55.6 AU/km) recorded significantly greater PlayerLoad than both U16 (242.7 ± 23.1 AU/km, $p<0.001$, ES=1.38, 95% CI=52.21-119.73) and U21 teams (235.1 ± 20.8 AU/km,

$p<0.001$, ES=1.46, 95% CI=61.07-120.58) respectively. The same condition was found in the 2-4 m s⁻¹ speed zone with the U18 team recording significantly greater PlayerLoad (336 ± 89.5 AU/km) than both U16 (211.6 ± 45 AU/km, $p<0.001$, ES=1.31, 95% CI=73.6-175.2) and U21 teams (266.5 ± 90.3 AU/km $p<0.001$, ES=0.73, 95% CI=6.69-132.31) respectively. No significant differences were recorded among teams across the three remaining speed zones.

Table 4.3. Total accumulated PlayerLoad (AU/km) in each speed zone.

Age	0-2.0 m s ⁻¹	2.0-4.0 m s ⁻¹	4.0-5.5 m s ⁻¹	5.5-7.0 m s ⁻¹	7.0-11.0 m s ⁻¹
U16	243 ± 23	211 ± 44	766 ± 261	3206 ± 1432	24683 ± 26431
U18	325 ± 55*	336 ± 89*	1282 ± 676	5126 ± 4307	23204 ± 28137
U21	235 ± 20	266 ± 90	1023 ± 574	4343 ± 4346	28111 ± 49286

* denotes significantly different ($p<0.05$) to both teams.

4.4 Discussion

This study examined the influence of playing age on the mechanical response to match play, to consider whether different teams within the same academy exhibit similar demands despite the potential change in players' attributes. The first parameter examined was distance, where the U16 team covered significantly greater distance in comparison to both U18 ($p<0.001$, ES 0.77, 95% CI=0.11-1.49) and U21 ($p<0.001$, ES=0.69, 95% CI=0.04-1.62) teams. Physical capacity improvements are typically linked with age but the results of this study do not fully support this observation (Buchheit et al., 2010a, 2010b; Papaiaikovou et al., 2009; Philippaerts et al., 2006).

As a result of the greater total distance covered, standardised for playing time, average speed exhibited significantly greater values for the U16 team (108.68 ± 9.79 m min⁻¹) in comparison to U18 (99.97 ± 11.18 m min⁻¹) and U21 teams (98.72 ± 14.04 m min⁻¹). With reference to tactical formation the club implemented a standardised system of play (4-4-2), of importance

as coaching styles and technical ability are factors that can affect style of play. The observation of greater distance covered in the youngest team is contrary to the research concerning the link between increased age with improvement in performance (Goto, Morris and Nevill, 2015; Harley et al., 2010).

The increased total distance, and subsequent average velocity observed in the U16 squad is attributed to greater distance covered in the 2-4 m s⁻¹ and 4-5.5 m s⁻¹ speed zones. At greater speeds the U16 team covered less distance but only approaching significance of $p=0.09$. The greater distance covered by the U16 team is attributed to the slow-to-mid-range speeds. The U21 team recorded a slight decrease in distance covered at higher speed zones, which might be indicative of a more tactical awareness and economy of movement. This data suggests a difference in pacing strategy, which is likely to be influenced by playing experience, but with implications for the physical demands.

The examination of the speed zone contribution ratio for the U16 team revealed a different style of movement. The increased percentage contribution at 2-4 m s⁻¹ was compromised by a lower percentage contribution at 0-2 m s⁻¹, representing a shift in style of play with less walking. The U16 team recorded the lowest percentage contribution at top speed, with the game played within a narrower speed band whereas the U18 and U21 teams play where speed fluctuates more (Buchheit et al., 2010a; Harley et al., 2010).

Literature suggests PlayerLoad is directly linked with total distance ($r=0.75$) (Casamichana and Castellano, 2015), however in the previous chapter this correlation coefficient was much reduced at $r=0.37$. In the present study the r -value ranged from 0.26-0.56, with evidence of higher coefficients in the U16 group. The U16s covered the greatest distance while the U18s recorded the greatest PlayerLoad, this lack of relationship between total distance and PlayerLoad is in agreement with the small-sided game observations of Aguiar *et al.* (2013) and Castellano *et al.* (2013). In the previous chapter a stronger correlation between PlayerLoad and

distance was attributed to a more frequent change in velocity and/or direction. The higher PlayerLoad observed in the U18s might therefore be indicative of greater magnitude of changes in acceleration. The higher correlation with distance in the U16s might be attributed to a more frequent change of direction and/or speed. The calculation of total accumulated PlayerLoad negates any indication of movement patterns.

PlayerLoad for the U18s was higher in each of the directional planes, resulting in the greater 3D load. However, the percentile contributions of each directional plane to total load reveal a unique movement strategy in the U18s. There was a significant decrease in the contribution of the vertical and antero-posterior planes, and a compensatory increase in the medio-lateral contribution to PlayerLoad. The movement footprint of U18 team revealed double the amount of medio-lateral force per match (U18 309.96 ± 45.82 AU vs. U16 141.49 ± 17.37 AU vs. U21 134.19 ± 17.99 AU). This suggests much greater time spent in sideways movement, although the calculation of Load does not differentiate between medial or lateral (left or right). Given the same team formation, this increased use of lateral movements is interesting and indicative of a change in style of play, but also a potential increased risk of injury.

An injury audit in academy football revealed joint sprains represented 66% of all injuries incurred with lower extremity injuries constituting 90% of all injuries reported (Price et al., 2004). Specifically, injuries sustained at the ankle were predominantly ligament strains (72%) and 34% of total injuries reported were sustained from non-contact activities including running and turning (Price et al., 2004). Injuries to the knee accounted for 18% of total injuries and 85% of these injuries were to the medial collateral ligament. Price *et al.* (2004) observed that the U19 team recorded the highest injury incidence rate in comparison to younger age groups, which would mirror the observations in this study. Soccer players experience 1000 changes in playing activity throughout a competitive match, and the U18 team in this study experienced more directional change than the U16 and U21 teams, thus creating implications for injury

(Reilly and Thomas, 1976). Additional insight on the movement pattern of the U18 team could be achieved with the inclusion of notational data to analyse where on the pitch the increased medio-lateral load is recorded.

PlayerLoad was highest for the U18s in all but the fastest speed zone. This again might be attributed to the increased utilisation of medio-lateral movements, which would be unlikely to occur at the highest speeds. High-speed directional changes would register a change in acceleration in both the antero-posterior and medio-lateral directions, however the highest speed zone entries are most likely linear sprints. Literature has recorded that the U18 age group covered greater very high-intensity running, sprinting distance and very high-intensity activity (Buchheit et al., 2010a). This supports observations in the present study where the U18s covered greater distance at the highest speed zone ($7-11 \text{ m s}^{-1}$) in line with the increased amount of sprints at equivalent speed zone per match (5.4 ± 4.3 efforts), highest amongst group (U16: 3.3 ± 3.4 efforts per match; U21: 4.8 ± 5 efforts per match). Therefore, establishing different speed zones for different ages can potentially provide a more indicative performance profile for youth soccer teams.

The influence of playing age suggests an increased demand from U16 to U18, but then a decrease in demand from U18 to U21. Indeed, the loading pattern of the U21s and U16s were very similar. The primary difference in these groups being a slower average velocity (and less total distance covered) in the U21s. The observed pattern might therefore be attributed with an increased physical capacity in the U18s vs U16s based on a greater training status and training history. Subsequently, with increased maturity and playing experience, a decrease in average running velocity at U21. One might even speculate that motivation might be a confounding factor, with U16s and U18s arguably at a heightened state of importance in their careers. Since the opposition is likely to affect the demands of the match, the U16s and U18s are at a stage in their club career where a contract is impending. The mechanical profile of the U16 team was

significantly different to the U18, however comparable to the U21 profile recorded. It is unlikely that the reduced demands of the U21s relative to the U18s are indicative of regression in physical status, however the increased loading apparent in the progression from U16 to U18, and particularly in medio-lateral loading, has implications for player development. There is evidence that PlayerLoad is correlated with injury rate (Gabbett and Ullah, 2012), and that playing in an older age group can significantly increase the risk of injury (Söderman et al., 2002). This concept of ‘playing up’ has implications for younger players who are progressed to older groups. The higher intensity recorded for the U18 age group most probably relates to a potentially higher risk of the U16 age group to sustain injuries as they develop through the academy team structure. The greater load recorded in the medio-lateral planes suggests the U18 team played soccer with increased emphasis on agility components rather than speed, with implications for injury epidemiology in youth football which highlights lateral joint sprains (Price et al., 2004). The multi-directional and intermittent profile of the U18 team is indicative of the rapid change in acceleration and direction associated with ACL and MCL risk.

4.5 Conclusion

Playing age had a considerable impact on the physical demands of match play. Whilst the U16s performed the greatest total distance, their activity profile was characterised by movements performed in the lower speed zones. The loading patterns of the U16s and U21s were very similar. In contrast the U18s exhibited significantly higher PlayerLoad, which was evident in all movement planes, and across all (bar the highest) speed zones. Further analysis revealed a significantly greater contribution from medio-lateral load, indicative of greater lateral and cutting movements. This change in movement pattern might also have implications for injury risk, with epidemiological observations in academy soccer highlighting this age group as particularly at risk. The most common mechanism of injury and the prominence of medio-

lateral joint sprains is also in line with observations of increased medio-lateral loading in this group. These findings have implications for the transition of youth players through a professional football club. This pattern in uni-axial loading further highlights the potential of GPS-based tri-axial accelerometry to inform practice when considering the biomechanical intensity of soccer. Quantifying external load with GPS technology aids in creating a player profile with physical and biomechanical load measures recorded (Aguiar et al., 2013; Scott et al., 2013). This technology can be utilised in creating player profiles with reference to age (Goto, Morris and Nevill, 2015; Harley et al., 2010) and playing position (Gonçalves et al., 2014).

CHAPTER 5. Comparison of PlayerLoad according to playing position

5.1 Introduction

The physical performance parameters have been well documented with outfield players covering approximately 10-12 km (Di Salvo et al., 2013). Appendix two provides a summary of distance covered according to various classifications of playing positions utilised in soccer research. The data reveals that midfielders tend to cover the greatest total distance during competitive matches in comparison to defenders and forwards (Di Salvo et al., 2013; Terje et al., 2016; Vigne et al., 2013; Wehbe, Hartwig and Duncan, 2013). The physical response to match play is also likely to be position-specific

Speed thresholds are examined in the majority of time-motion analysis studies, with data varying across playing position, providing a physical measure of performance for assessment. Specifically, analysis of total distance covered in high-speed running (>19.8 km/h) showed that wide midfielders ran a significantly greater distance compared to the other playing positions and also covered the largest distance overall suggesting they were subjected to substantially higher physical demands (Bradley et al., 2009). Similarly, the positional analysis of sprinting actions (>25.2 km/h) categorised according to acceleration characteristics shows that fullbacks, wide midfielders and attackers performed significantly more explosive-type sprints than central defenders and midfielders respectively (Bradley et al., 2009). The implications suggest further refinement of positional-specific physical training (Carling, Dupont and Le Gall, 2012; Di Mascio and Bradley, 2013; Di Salvo et al., 2007; Mohr, Krstrup and Bangsbo, 2003). The categorisation of playing position might also be an influencing factor, with team formation influencing the activity profile of a 'midfielder'. For example, in a 4-4-2 formation the midfielders would have a different central vs wide remit than in a 4-3-3 formation, for example.

The traditional 'unit' descriptors of defender, midfielder, forward fails to consider the impact of positional width on the physical demands.

Recently, Barron *et al.* (2014) applied this positional analysis to youth soccer, further incorporating measures of PlayerLoad. Thirty-eight youth college players (Age: 17.3 ± 0.9 y; Height 177 ± 6 cm; body mass 71.3 ± 8.1 kg) were analysed during eight college matches with the use of portable 5Hz GPS units. Centre midfielders covered the greatest total distance during acceleration periods, while centre defenders covered the least, thus demonstrating similarities with senior elite soccer. PlayerLoad derived from the GPS units revealed significantly greater load exhibited by central midfielders than central defenders. Intuitively this increased PlayerLoad might be attributed to the increased distance travelled, but the authors failed to standardise PlayerLoad for distance travelled and the sub-elite standard of the players also limits generalisability toward an elite population.

In contrast to the players used by Barron *et al.*, the present thesis is specifically relevant to the context of an elite academy. The higher level of player and greater number of matches analysed in the present study is developed further by considering a more rigorous classification of playing position than previous research (Barron *et al.*, 2014). In elite youth soccer it is anticipated that each playing position will be characterised by its unique technical and tactical remit, and thus will exhibit unique physical demands. In the present study the tri-axial analysis of PlayerLoad is used to investigate the influence of playing position on the mechanical response to match play. This is conducted in a single age group, given the disparity observed in the previous Chapter. The aims of this study are: (1) to quantify the influence of playing position on the physical demands of match play, and (2) to consider the sensitivity of positional grouping (i.e. defenders, midfielders, forwards).

5.2 Methodology

Participants

Performance was analysed during match play for players belonging to a Premier League soccer academy (same cohort as chapters three and four). The analyses of players in a high performance environment during official match play aimed to enhance and ensure strong ecological validity across this study. It is evident from soccer research (Barron et al., 2014; Bradley et al., 2011; Di Salvo et al., 2007, Di Salvo et al., 2013) that there are various categorisations of playing position. This difference is a result of the tactical demands of various leagues, making the elite academy analysed in this thesis a unique population.

Analyses were performed over the course of one season (2011-2012). Over this period 113 datasets were collected from 32 male outfield players (Age: 17.2 ± 0.7 y; Height: 177 ± 6 cm; body mass: 73.2 ± 6.4 kg) who completed 90 min of competitive matches (n=17). Initial analysis of data involved distributing players into three playing positions; defenders (n=49), midfielders (n=28) and forwards (n=36). To further analyse the data more specifically, a secondary analysis involved the inclusion of additional positions; centre backs (n=26), full backs (n=23), wingers (n=14), and centre forwards (n=22).

The experimental approach in terms of sample size from a restricted population of this study and the potential statistical power of the results and the extent to which findings are applicable to other soccer environments could be potential limitations of this study. It has been concluded that a sample size containing 80 players is suggested to provide sufficient statistical power to enable meaningful detection of real systematic differences in match play physical performance and takes into consideration the natural variability in physical activity across games (Gregson, Drust and Atkinson, 2010).

Over the course of this work, player consent and approval by the football club for all the studies were obtained. These data arose as a condition of employment in which player performance was routinely measured over the course of the competitive season (Winter and Maughan, 2009). All match performance-related data were anonymised before analysis to ensure team and player confidentiality. Players included in this study were coded according to playing position.

Categorisation of playing position

From a tactical perspective, the academy where this data was collected may not fulfill the criteria of the traditional 4-4-2 style of play. Therefore, a more discrete categorisation of positions is required to reflect tactical adjustments. These findings have implications for the classification of playing position for the prescription of physical training regimes, and highlight the specific mechanical demands of each position. Tactical and technical demands are likely to change both the physical and biomechanical intensity of match play.

Motion analysis and data collection techniques

Players were fitted with a 10Hz GPS unit (MinimaxX S4, Catapult Innovations, Canberra, ACT, Australia) prior to kick-off. The units were worn between the shoulder blades in a custom made undergarment. The accuracy and reliability of GPS is relatively high: results of a test of accuracy showed a 4.8% error rate in measuring total distance covered (Edgecomb and Norton, 2006). Research suggests that GPS with a higher frequency rate provides greater validity for measurement of distance. GPS units with a 10Hz sampling frequency can measure the smallest change in acceleration and deceleration while the 5Hz GPS units are unable to record this (Varley, Fairweather and Aughey, 2012). During running ($\approx 6 \text{ m}\cdot\text{s}^{-1}$) the standard error of estimate reported is 5.6% (Portas et al., 2010). However, GPS units with increased sampling frequency (10Hz in this study) demonstrate improved reliability and validity allowing for usage

in monitoring activities in team sports (Cummins et al., 2013). Raw data from all game analyses were extracted from the service provider and collated using Microsoft Excel.

Match performance measures

Over the course of this work, information on physical performance was collected. Measures of physical performance included analysis of the total distances (difference between 1st and 2nd half) covered at a range of running speeds (0.2-2 m·s⁻¹, 2-4 m·s⁻¹, 4-5.5 m·s⁻¹, 5.5-11 m·s⁻¹). The two highest speed zones for soccer include sprint distance and high-speed distance which is greater than 5.5 m·s⁻¹ and 7 m·s⁻¹ respectively (Bangsbo, Mohr and Krstrup, 2006; Bradley et al., 2013). Classification of speed zones provides precise comparisons of performance between soccer players. The speed zones are distributed in activity bands and the upper zones (4-6) provide more insightful information on the physical demands experienced by players (Cummins et al., 2013). Abt and Lovell (2009) argued for the requirement of individual high-intensity speed thresholds since players produce different speed when they begin high-intensity efforts. However, this suggestion postulates both logical and logistical problem in speed zone determination (Bangsbo, Mohr and Krstrup, 2006). In addition, to formulate the biomechanical formula of playing position, PlayerLoad was calculated across the three-acceleration planes antero-posterior (y), medio-lateral (x) and vertical (z) for a 90 min game. Therefore, data was uniform and valid conclusions will be able to be made. In addition, load was divided by distance covered in order to assess 'load economy' or how efficient players moved biomechanically in each playing position analysed.

Statistical Procedures and Tests

In a large body of motion analysis studies simple inferential statistical testing is the method used to explore data sets from games analyses of physical performance (Abt and Lovell, 2009;

Barros et al., 2007; Bloomfield, Polman and O'Donoghue, 2007; Bradley et al., 2009; Bradley et al., 2010; Castagna et al., 2009).

In the study descriptive statistics for all raw and normalised variables were calculated and reported as means and standard deviations (mean \pm SD). A repeated measures analysis of variance (ANOVA) was employed to investigate differences in mean scores across the different measures of physical performance in each playing position category. Measure of Cohen's d effect size and 95% confidence intervals were reported for the mean difference for pairwise comparisons. The relationship between PlayerLoad and total distance was assessed using the Pearson's correlation coefficient. Magnitude of correlation coefficients was considered as trivial ($r < 0.1$), small ($0.1 < r < 0.3$), moderate ($0.3 < r < 0.5$), large ($0.5 < r < 0.7$), very large ($0.7 < r < 0.9$), almost perfect ($r > 0.9$) or perfect ($r = 1$; Hopkins, 2002). All the statistical analyses were performed using SPSS 20 (IBM, 2013) for Mac OS (Apple Computer), with significance being set at $p \leq 0.05$.

5.3 Results

Figure 5.1 presents the total distance covered (km) recorded of defenders, midfielders and forwards during competitive matches. Defenders covered significantly less distance (8.9 ± 0.9 km) than midfielders (9.4 ± 1.3 km, $p = 0.039$, ES=0.5, 95% CI=-1.0 to -0.0) and forwards (9.8 ± 1.0 km, $p < 0.001$, ES=0.9, 95% CI=-1.3 to -0.5).

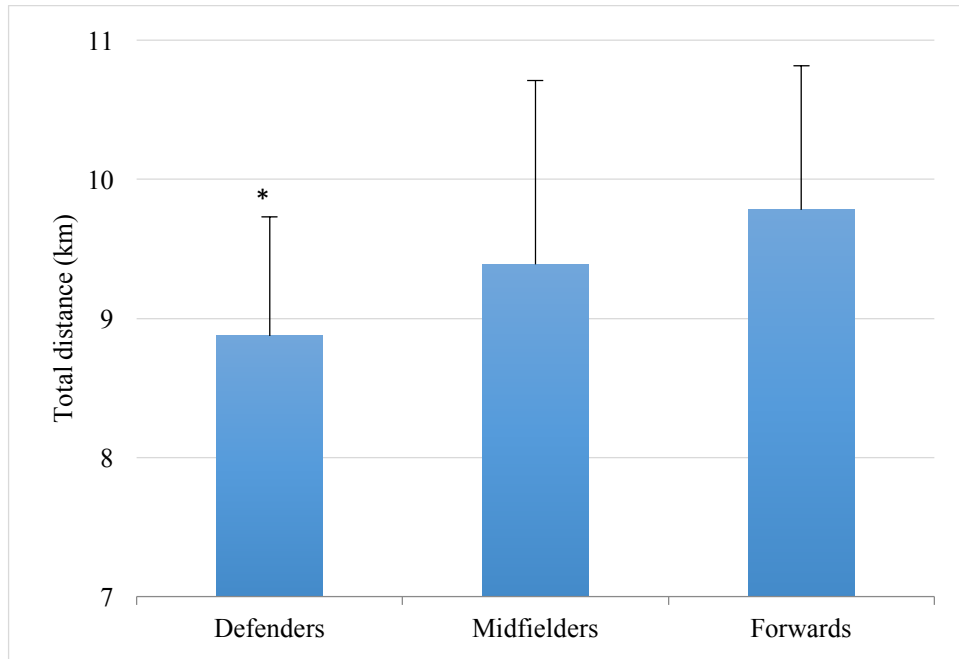


Figure 5.1. Total distance covered of defenders, midfielders and forwards.

* denotes significantly different ($p < 0.05$) to other positions.

Figure 5.2 provides a summary of total distance covered during competitive matches of wide defenders, central defenders, midfielders, wide attackers and centre forwards. Both defensive positions (wide and central defenders) recorded the least total distance. Specifically, wide defenders covered significantly less total distance (9.1 ± 0.7 km) than centre forwards (9.9 ± 1.2 km, $p = 0.006$, $ES = 0.8$, 95% $CI = -1.5$ to -0.3) while central defenders covered significantly less total distance (8.7 ± 0.9 km) than midfielders (9.4 ± 1.1 km, $p = 0.016$, $ES = 0.6$, 95% $CI = -1.3$ to -0.1), wide attackers (9.5 ± 0.8 km, $p = 0.017$, $ES = 0.9$, 95% $CI = -1.4$ to -0.3) and centre forwards ($p < 0.001$, $ES = 1.0$, 95% $CI = -1.9$ to -0.6).

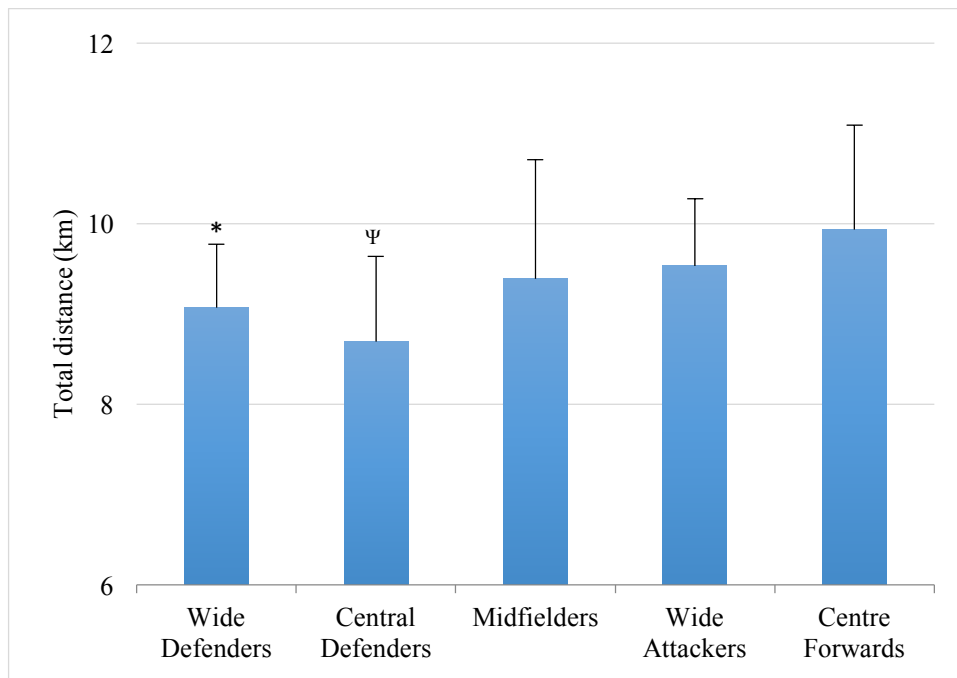


Figure 5.2. Total distance covered of wide defenders, central defenders, midfielders, wide attackers and centre forwards.

* denotes significantly different ($p < 0.05$) to centre forwards.

Ψ denotes significantly different ($p < 0.05$) to midfielders, wide attackers and centre forwards.

Table 5.1 presents total distance values during the first and second half of competitive soccer matches of all positions analysed (defenders, midfielders, forwards, wide defenders, central defenders, wide attackers and centre forwards).

Table 5.1. Mean \pm SD total distance covered (m) during 1st and 2nd half.

Playing Position	1 st half	2 nd half	% Difference (m) 95% CI
Defenders	4477 \pm 430	4398 \pm 482	-1.8 (79 m) -106.1 to 264.1
Midfielders	4818 \pm 784	4570 \pm 604	-5.1 (248m) -134.2 to 630.2
Forwards	5069 \pm 536	4712 \pm 535	-7 (357m) 108.8 to 605.2
Wide Defenders	4525 \pm 409	4549 \pm 356	+0.5 (24 m) -262.1 to 215.1
Central Defenders	4435 \pm 451	4264 \pm 542	-3.9 (171 m) -101.3 to 443.3
Wide Attackers	4891 \pm 350	4638 \pm 482	-5.2 (253 m) -51.1 to 557.1
Centre Forwards	5182 \pm 607	4759 \pm 573	-8.2 (423 m) 54.9 to 791.2

Figure 5.3 is a summary of high-speed distance covered (5.5-11.0 m s⁻¹) during competitive matches. Forwards recorded significantly greater high-speed distance (604.8 \pm 165.1 m) than midfielders (320 \pm 203.9 m, $p < 0.001$, ES=1.2, 95% CI=192.6 to 377.2) and defenders (424.7 \pm 205.9 m, $p < 0.001$, ES=0.9, 95% CI=97.8 to 262.6). Midfielders covered significantly less high-speed distance than defenders ($p = 0.024$, ES=0.5, 95% CI=6.4 to 203.1).

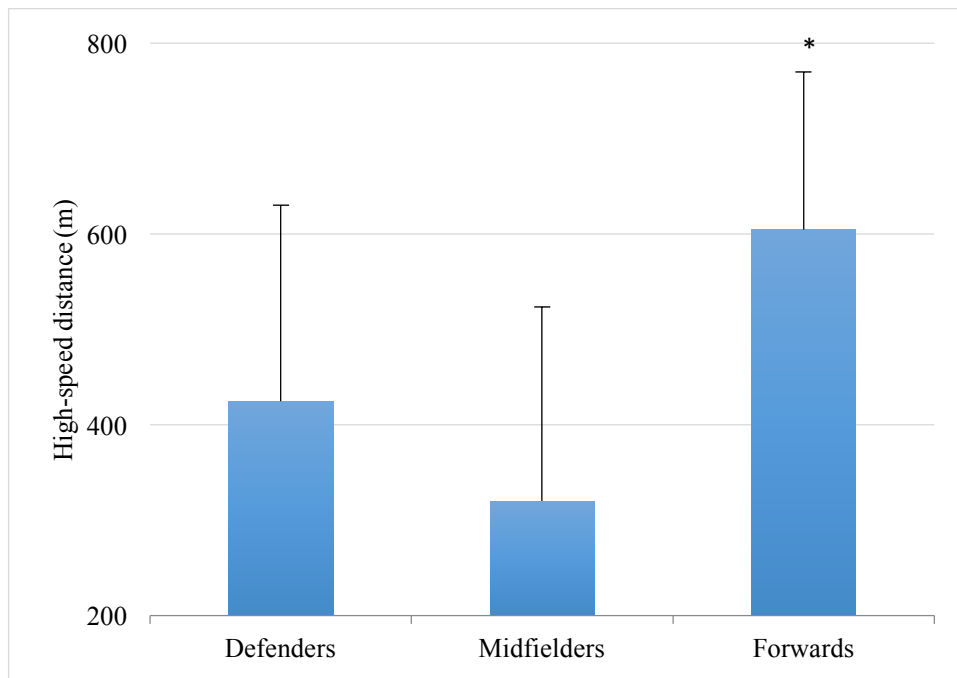


Figure 5.3. High-speed ($5.5\text{-}11\text{ m s}^{-1}$) distance covered of defenders, midfielders and forwards.

* denotes significantly different ($p<0.05$) to other positions.

Comparisons between playing positions (wide defenders, central defenders, midfielders, wide attackers and centre forwards) for high-speed distance ($5.5\text{-}11\text{ m s}^{-1}$) are shown in Figure 5.4. Wide defenders covered significantly greater high-speed distance ($530.6 \pm 171.5\text{ m}$) than both central defenders ($331.1 \pm 189.8\text{ m}$, $p<0.001$, $\text{ES}=1.1$, $95\%\text{ CI}=92.9\text{ to }306.2$) and midfielders ($320 \pm 203.9\text{ m}$, $p<0.001$, $\text{ES}=1$, $95\%\text{ CI}=99.\text{ to }322.2$). Central defenders covered significantly less high-speed distance than wide attackers ($567.5 \pm 170.3\text{ m}$, $p<0.001$, $\text{ES}=1.2$, $95\%\text{ CI}=-353\text{ to }-120$) and centre forwards ($628.6 \pm 161.15\text{ m}$, $p<0.001$, $\text{ES}=1.4$, $95\%\text{ CI}=-401.8\text{ to }-193.5$). Midfielders covered significantly less high-speed distance than wide attackers ($p<0.001$, $95\%\text{ CI}=-370.1\text{ to }-125$) and centre forwards ($p<0.001$, $95\%\text{ CI}=-417.9\text{ to }-199.4$).

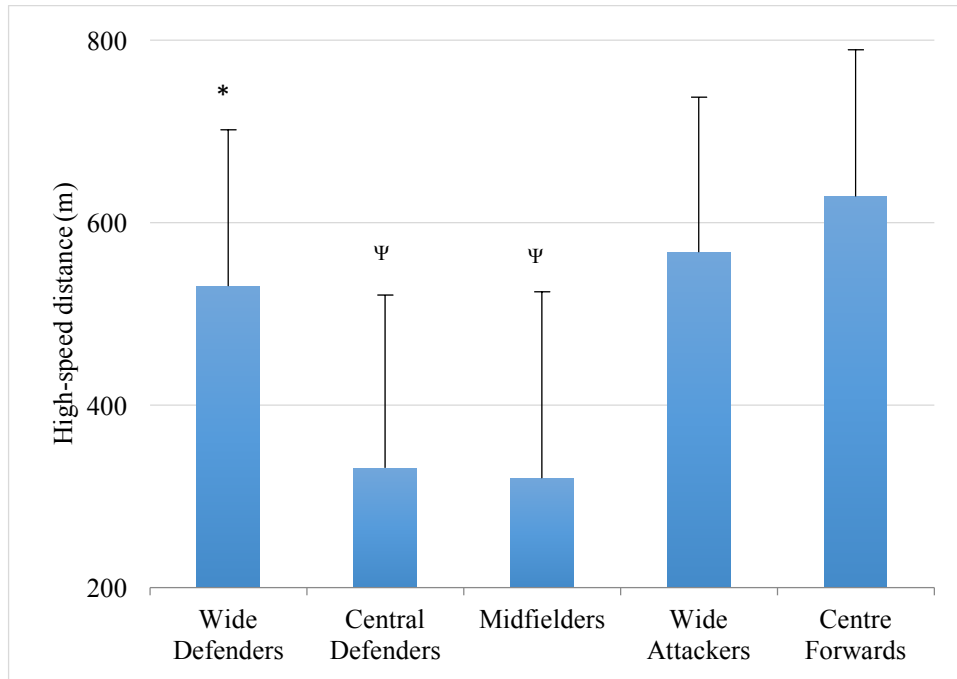


Figure 5.4. High-speed ($5.5-11 \text{ m s}^{-1}$) distance covered of wide defenders, central defenders, midfielders, wide attackers and centre forwards.

* denotes significantly different ($p < 0.05$) to central defenders and midfielders.

Ψ denotes significantly different ($p < 0.05$) to wide attackers and centre forwards.

Table 5.2 provides a summary of the speed zone specific distance covered for all positions. Central defenders covered significantly less distance at a speed of $0-2 \text{ m s}^{-1}$ than wide defenders ($p=0.001$, $ES=1$, $95\% \text{ CI}=-471$ to -145), midfielders ($p=0.008$, $ES=0.6$, $95\% \text{ CI}=-414.9$ to -47.1), and wide attackers ($p < 0.001$, $ES=1.3$, $95\% \text{ CI}=-527.1$ to 246.9). Wide attackers covered significantly greater distance at a speed of $0-2 \text{ m s}^{-1}$ than centre forwards ($p=0.004$, $ES=1.1$, $95\% \text{ CI}=143$ to 491). Defenders covered significantly less distance at a speed of $2-4 \text{ m s}^{-1}$ than midfielders ($p=0.11$, $ES=0.5$, $95\% \text{ CI}=-845.5$ to -114.5) and forwards ($p=0.013$, $ES=0.5$, $95\% \text{ CI}=-754.3$ to -119.7). Wide defenders covered significantly less distance at a speed of $2-4 \text{ m s}^{-1}$ than midfielders ($p=0.005$, $ES=0.7$, $95\% \text{ CI}=-769.3$ to 357.3) and centre forwards ($p=0.004$, $ES=0.8$, $95\% \text{ CI}=-823.3$ to 291.3). Forwards covered significantly greater distance at a speed of $4-5.5 \text{ m s}^{-1}$ than defenders ($p < 0.001$, $ES=0.9$, $95\% \text{ CI}=188.3$ to 465.7) and midfielders ($p=0.003$, $ES=0.6$, $95\% \text{ CI}=49.2$ to 464.8). Centre forwards covered significantly greater

distance at a speed of 4-5.5 m s⁻¹ than wide defenders ($p=0.001$, ES=1, 95% CI=156.1 to 543.9), wide attackers ($p=0.037$, ES=0.7, 95% CI=11.2 to 478.8), central defenders ($p<0.001$, ES=1.4, 95% CI=312.1 to 659.9) and midfielders ($p<0.001$, ES=0.9, 95% CI=108 to 596). Forwards covered significantly greater distance at a speed of 5.5-11 m s⁻¹ than defenders ($p<0.001$, ES=0.9, 95% CI=97.6 to 262.4) and midfielders ($p<0.001$, ES=1.6, 95% CI=192.7 to 377.3). Midfielders covered significantly less distance at a speed of 5.5-11 m s⁻¹ than wide defenders ($p<0.001$, ES=1, 95% CI=-322.7 to -99.3), wide attackers ($p<0.001$, ES=1.1, 95% CI=-370.5 to -125.5) and centre forwards ($p<0.001$, ES=1.3, 95% CI=-415.2 to -196.8).

Table 5.2. Mean \pm SD total distance covered in speed zones (m).

Playing Position	0 – 2 m s ⁻¹	2 – 4 m s ⁻¹	4 – 5.5 m s ⁻¹	5.5 – 11 m s ⁻¹
Defenders	3730 \pm 321	3651 \pm 573	1026 \pm 282	425 \pm 206
Midfielders	3817 \pm 434	4121 \pm 1019	1096 \pm 471	320 \pm 204
Forwards	3780 \pm 299	4078 \pm 893	1353 \pm 361	605 \pm 165
Wide Defenders	3894 \pm 358	3507 \pm 519	1098 \pm 287	531 \pm 172
Central Defenders	3586 \pm 196	3780 \pm 598	962 \pm 266	331 \pm 190
Wide Attackers	3973 \pm 256	3915 \pm 882	1203 \pm 365	568 \pm 170
Centre Forwards	3656 \pm 260	4181 \pm 905	1448 \pm 333	629 \pm 161

The differences in total and uni-axial PlayerLoad between defenders, midfielders and forwards during competitive games are shown in Figure 5.5. Midfielders recorded similar vertical load (613 \pm 77 AU) to forwards (579 \pm 101 arbitrary units, $p=0.051$, ES=0.4, 95% CI=-12.5 to 80.7) and significantly greater vertical load to defenders (542.5 \pm 71.9 AU, $p=0.001$, ES=0.9, 95%

CI=35.1 to 105.8). Anterio-posterior load revealed similar values for midfielders (400 ± 66 AU) in comparison to defenders (367 ± 89 AU, $p=0.067$, ES=0.4, 95% CI=-6.5 to 71.7) while significantly greater load to forwards (356 ± 56 AU, $p=0.020$, ES=0.7, 95% CI=13.7 to 74.7). Defenders recorded significantly less medio-lateral load (297 ± 41 AU) to midfielders (336 ± 49 AU, $p<0.001$, ES=0.8, 95% CI=-58.5 to -19.7) and forwards (322 ± 44 AU, $p=0.010$, ES=0.6, 95% CI=-53.6 to -16.9). Midfielders recorded significantly greater total tri-axial PlayerLoad (1350.1 ± 144.5 AU) than defenders (1207 ± 156 AU, $p<0.001$, ES=0.9, 95% CI=70.5 to 216.2) and forwards (1256 ± 172 AU, $p=0.021$, ES=0.6, 95% CI=12.2 to 175.1).

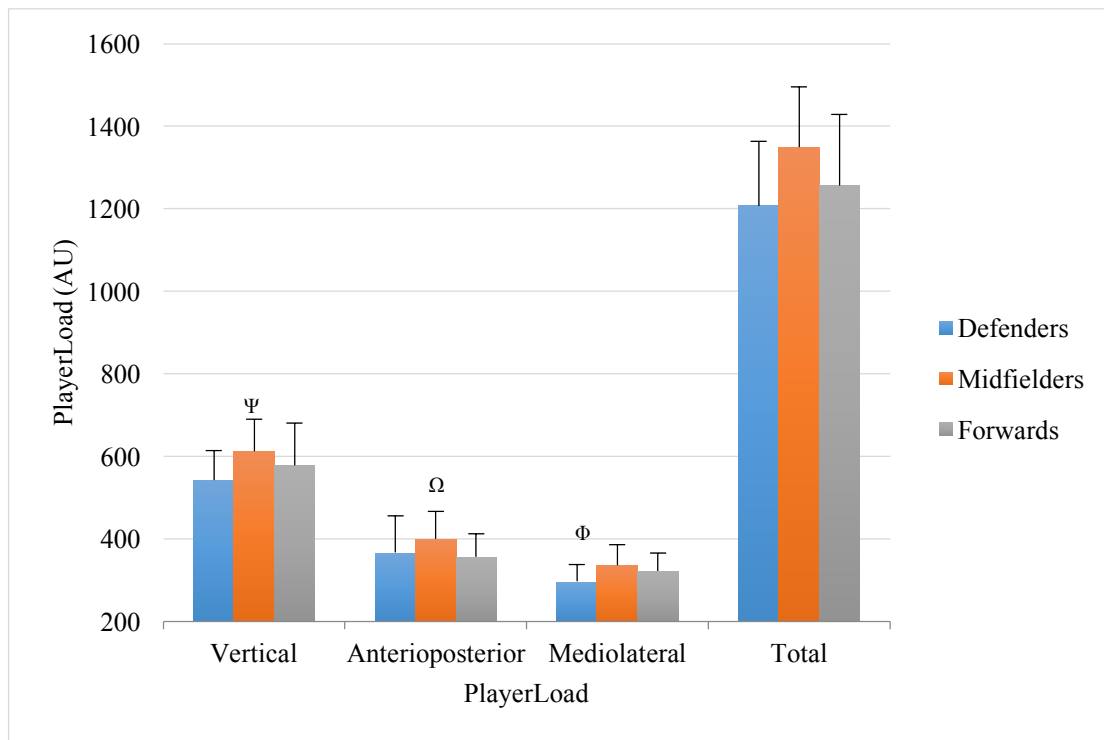


Figure 5.5. Total and uni-axial PlayerLoad of defenders, midfielders and forwards.

* denotes significantly different ($p<0.05$) to other positions.

Ψ denotes significantly different ($p<0.05$) to defenders.

Ω denotes significantly different ($p<0.05$) to forwards.

Φ denotes significantly different ($p<0.05$) to other positions.

Figure 5.6 summarises the loading patterns for the positional categories of wide defenders, central defenders, midfielders, wide attackers and centre forwards during competitive matches. Both defensive positions recorded the lowest vertical load values. Specifically, wide defenders produced significantly less vertical load (537.1 ± 94.7 AU) than midfielders (613 ± 77.1 AU, $p=0.002$, ES=0.8, 95% CI=-125.8 to -26) and centre forwards (589.6 ± 116.4 AU, $p=0.039$, ES=0.5, 95% CI=-118.7 to 13.7) while central defenders recorded significantly less vertical load (547.4 ± 44.5 AU) than midfielders ($p=0.005$, ES=0.9, 95% CI=-100 to -31.2). Wide attackers did not yield any significant differences among positions for vertical load (562.1 ± 73.8 AU). The values for antero-posterior load of each playing position were as follows, wide defenders, (382.5 ± 100 AU), central defenders (353.9 ± 77.5 AU), midfielders (399.9 ± 65.9 AU), wide attackers (378.5 ± 33.8 arbitrary units) and centre forwards (341.1 ± 62.7 AU). Central defenders yielded significantly less antero-posterior load than midfielders ($p=0.024$, ES=0.6, 95% CI=-85.3 to -6.7), while centre forwards recorded significantly less than midfielders ($p=0.006$, ES=0.8, 95% CI=-96.6 to -20.9). Wide defenders yielded significantly less medio-lateral load (295.7 ± 55.3 AU) than midfielders (336 ± 49.2 AU, $p=0.001$, ES=0.7, 95% CI=-70.7 to -9.8) and wide attackers (342.6 ± 26.6 AU, $p=0.002$, ES=0.9, 95% CI=-77.4 to -16.4). Similarly, central defenders yielded significantly less medio-lateral load (297.9 ± 22 AU) than midfielders ($p=0.002$, ES=0.9, 95% CI=-61.3 to -14.8) and wide attackers ($p=0.002$, ES=1.4, 95% CI=-60.9 to -28.5). Centre forwards recorded significantly less medio-lateral load (309.1 ± 48.3 arbitrary units) than midfielders ($p=0.032$, ES=0.5, 95% CI=-55.5 to 1.7) and wide attackers ($p=0.026$, ES=0.8, 95% CI=-60.8 to -6.3). Midfielders yielded significantly greater tri-axial PlayerLoad (1350.1 ± 144.5 AU) than wide defenders (1215.3 ± 203.2 AU, $p=0.003$, ES=0.7, 95% CI=33.9 to 235.9), central defenders (1199.3 ± 101.5 AU, $p=0.001$, ES=1, 95% CI=82.6 to 219) and centre forwards (1239.6 ± 200.2 AU, $p=0.017$, ES=0.6, 95%

CI=10.4 to 210.7). Wide attackers were not significantly different to other positions for tri-axial PlayerLoad (1283.1 ± 117.1 AU).

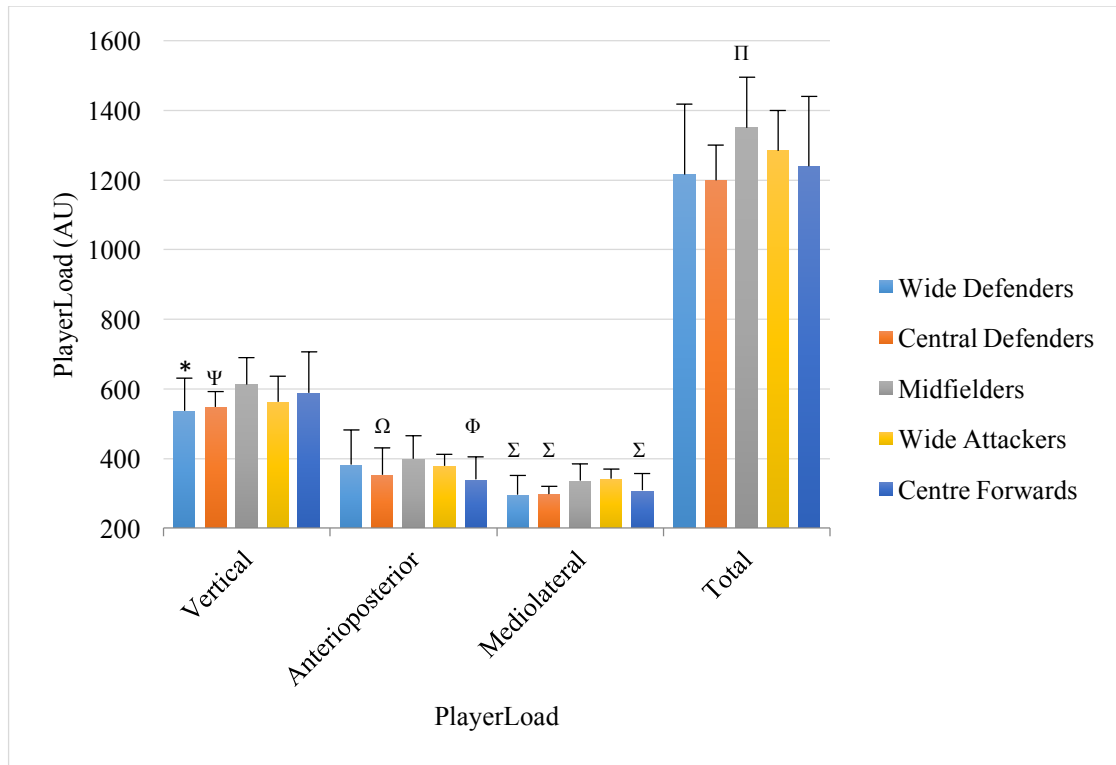


Figure 5.6. Total and uni-axial PlayerLoad of wide defenders, central defenders, midfielders, wide attackers and centre forwards.

* denotes significantly different ($p < 0.05$) to midfielders and centre forwards.

Ψ denotes significantly different ($p < 0.05$) to midfielders.

Ω denotes significantly different ($p < 0.05$) to midfielders.

Φ denotes significantly different ($p < 0.05$) to midfielders.

Σ denotes significantly different ($p < 0.05$) to midfielders and wide attackers.

Π denotes significantly different ($p < 0.05$) to wide defenders, central defenders and centre forwards.

Table 5.3 summarises the correlation coefficient for a linear regression of PlayerLoad vs total distance covered for each positional category. In all cases $p < 0.001$.

Table 5.3. Regression correlation strength between PlayerLoad and distance.

Playing Position	1 st half	2 nd half ^d
Defenders	0.41	0.48
Midfielders	0.16	0.31
Forwards	0.74	0.67
Wide Defenders	0.51	0.63
Central Defenders	0.36	0.41
Wide Attackers	0.39	0.45
Central Forwards	0.85	0.82

Figure 5.7 is a summary of tri-axial PlayerLoad per kilometer of distance covered for defenders, midfielders and forwards. Midfielders recorded significantly greater total PlayerLoad per kilometer (147.9 ± 34.8 AU/km) than defenders (136.6 ± 17.3 AU/km, $p=0.003$, ES=0.4, 95% CI=-0.7 to 23.3) and forwards (128.6 ± 13.4 AU/km, $p=0.001$, ES=0.7, 95% CI=6.8 to 31.9). Forwards covered significantly less anteroposterior load per kilometer (36.4 ± 5.4 AU/km) than defenders (41.6 ± 10 AU/km, $p=0.018$, ES=0.6, 95% CI=-8.8 to -1.6) and midfielders (44.1 ± 13 AU/km, $p=0.002$, ES=0.8, 95% CI=-12.4 to -3). Midfielders covered significantly greater mediolateral load per kilometer (36.9 ± 9.9 AU/km) than defenders (33.6 ± 4.7 , $p=0.03$, ES=0.5, 95% CI=-0.1 to 6.7) and forwards (33.1 ± 4.5 AU/km, $p=0.018$, ES=0.5, 95% CI=0.2 to 7.5). Midfielders recorded significantly greater vertical load per kilometer (66.8 ± 14.1 AU/km) than defenders (61.4 ± 7.8 AU/km, $p=0.019$, ES=0.5, 95% CI=0.4 to 10.4) and forwards (59.0 ± 7 AU/km, $p=0.002$, ES=0.7, 95% CI=2.4 to 13.1).

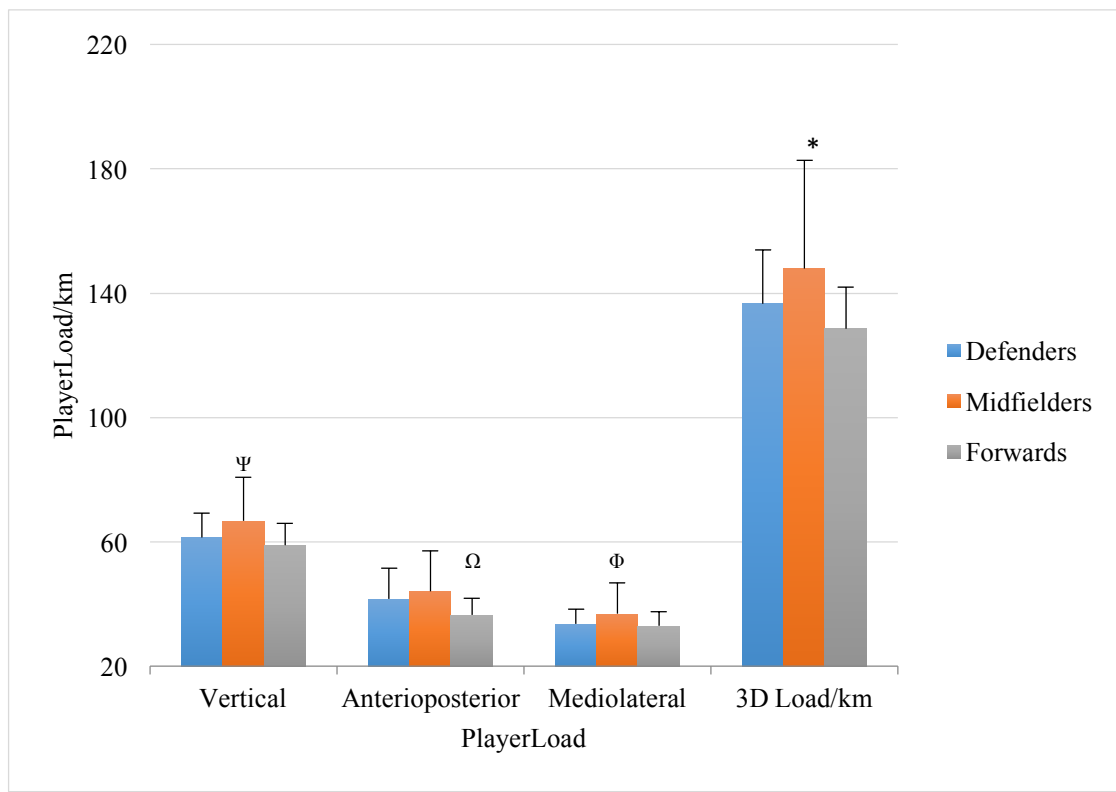


Figure 5.7. Total and uni-axial PlayerLoad per kilometer of defenders, midfielders and forwards.

* denotes significantly different ($p < 0.05$) to other positions.

Ψ denotes significantly different ($p < 0.05$) to other positions.

Ω denotes significantly different ($p < 0.05$) to other positions.

Φ denotes significantly different ($p < 0.05$) to other positions.

Figure 5.8 provides a summary of tri-axial PlayerLoad per kilometer of distance covered of wide defenders, central defenders, midfielders, wide attackers and centre forwards. Midfielders recorded significantly greater vertical load per kilometer (66.8 ± 14.1 AU/km) than wide defenders (59.1 ± 8.4 AU/km, $p = 0.005$, $ES = 0.6$, $95\% \text{ CI} = 0.7$ to 14.7), wide attackers (59.1 ± 7.7 AU/km, $p = 0.016$, $ES = 0.6$, $95\% \text{ CI} = -0.2$ to 15.4) and centre forwards (59.0 ± 6.7 AU/km, $p = 0.005$, $ES = 0.7$, $95\% \text{ CI} = 1.1$ to 14.6). Centre forwards recorded significantly less anterioposterior load per kilometer (34.4 ± 5.1 AU/km) than wide defenders (42.2 ± 10.3 arbitrary

units per kilometer, $p=0.008$, $ES=0.9$, 95% $CI=-12.9$ to -2.8), central defenders (41.1 ± 9.9 AU/km, $p=0.018$, $ES=0.8$, 95% $CI=-11.5$ to -1.9) and midfielders (44.1 ± 13 AU/km, $p=0.001$, $ES=0.9$, 95% $CI=-15.8$ to -3.7). Midfielders produced significantly greater medio-lateral load per kilometer (36.9 ± 9.9 AU/km) than wide defenders (32.5 ± 5.1 AU/km, $p=0.013$, $ES=0.5$, 95% $CI=-0.5$ to 9.3) and centre forwards (31.1 ± 3.8 AU/km, $p=0.001$, $ES=0.7$, 95% $CI=1.1$ to 10.5). Wide attackers yielded significantly greater medio-lateral load per kilometer (36.2 ± 4 AU/km) than centre forwards ($p=0.019$, $ES=1.1$, 95% $CI=2.6$ to 7.4). Tri-axial PlayerLoad per kilometer was significantly greater for midfielders (147.9 ± 34.8 AU/km) in comparison to wide defenders (133.8 ± 18.5 AU/km, $p=0.024$, $ES=0.5$, 95% $CI=-2.8$ to 31.1) and centre forwards (124.4 ± 11.6 AU/km, $p=0.001$, $ES=0.8$, 95% $CI=7.5$ to 39.5). Centre forwards had a significantly less tri-axial PlayerLoad per kilometer than central defenders (139.1 ± 16.2 AU/km, $p=0.023$, $ES=0.9$, 95% $CI=-23.1$ to -6.3).

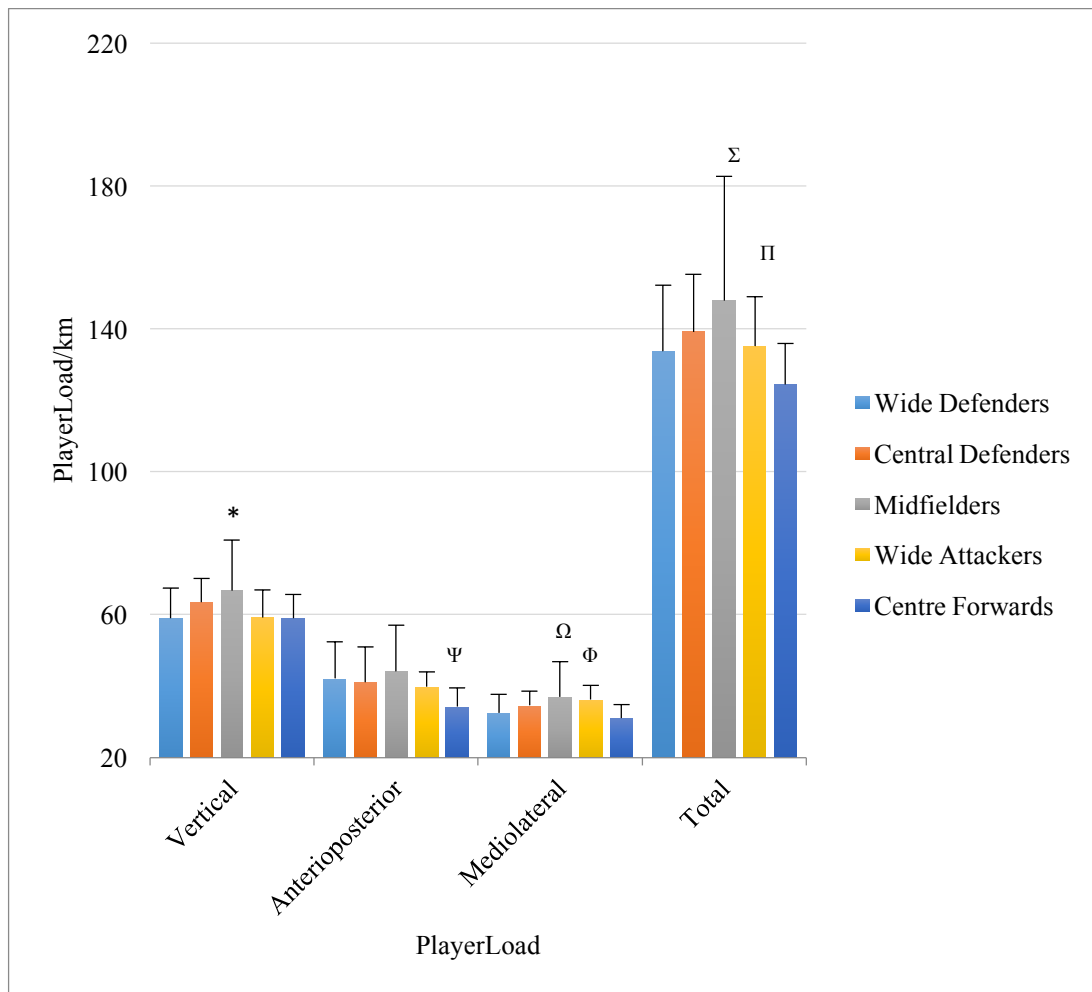


Figure 5.8. Total and uni-axial PlayerLoad per kilometer of wide defenders, central defenders, midfielders, wide attackers and centre forwards.

* denotes significantly different ($p < 0.05$) to wide defenders, wide attackers and centre forwards.

Ψ denotes significantly different ($p < 0.05$) to wide defenders, central defenders and midfielders.

Ω denotes significantly different ($p < 0.05$) wide defenders and centre forwards.

Φ denotes significantly different ($p < 0.05$) to centre forwards.

Σ denotes significantly different ($p < 0.05$) wide defenders and centre forwards.

Π denotes significantly different ($p < 0.05$) to central defenders.

Figure 5.9 provides a summary of tri-axial PlayerLoad per kilometer of high-speed distance (km HSD: 5.5-11 m·s⁻¹) covered during competitive matches for defenders, midfielders and forwards. Midfielders had significantly greater vertical load per kilometer of high-speed distance (3825 ± 4383.9 arbitrary units per km HSD) than defenders (1683 ± 1073.3 AU/km HSD, $p < 0.001$, ES=1, 95% CI=666.3 to 3617.7) and forwards (1062.2 ± 484.5 AU/km HSD, $p < 0.001$, ES=1.2, 95% CI=1314.3 to 4211.2). Midfielders recorded significantly greater medio-lateral load per kilometer of high-speed distance (2261.3 ± 2771.1 AU/km HSD) than defenders (924.4 ± 597 AU/ km HSD, $p < 0.001$, ES=0.7, 95% CI=511.5 to 2162.4) and forwards (588.6 ± 248.5 AU/km HSD, $p < 0.001$, ES=0.8, 95% CI=759.7 to 2585.7). Midfielders recorded significantly greater antero-posterior load per kilometer of high-speed distance (2717.1 ± 3354.3 AU/km HSD) than defenders (1127.6 ± 689.5 AU/km HSD, $p < 0.001$, ES=1, 95% CI=593.8 to 2585.3) and forwards (656 ± 292.4 AU/km HSD, $p < 0.001$, ES=1.2, 95% CI=956.3 to 3165.9). Tri-axial PlayerLoad per kilometer of high-speed distance was significantly greater for midfielders (8821 ± 10469.6 AU/km HSD) in comparison to defenders (3735.3 ± 2311.5 AU/km HSD, $p < 0.001$, ES=0.7, 95% CI=1960.8 to 8210.5) and forwards (2307.1 ± 1011.8 AU/km HSD, $p < 0.001$, ES=0.9, 95% CI=3061.5 to 9966.3).

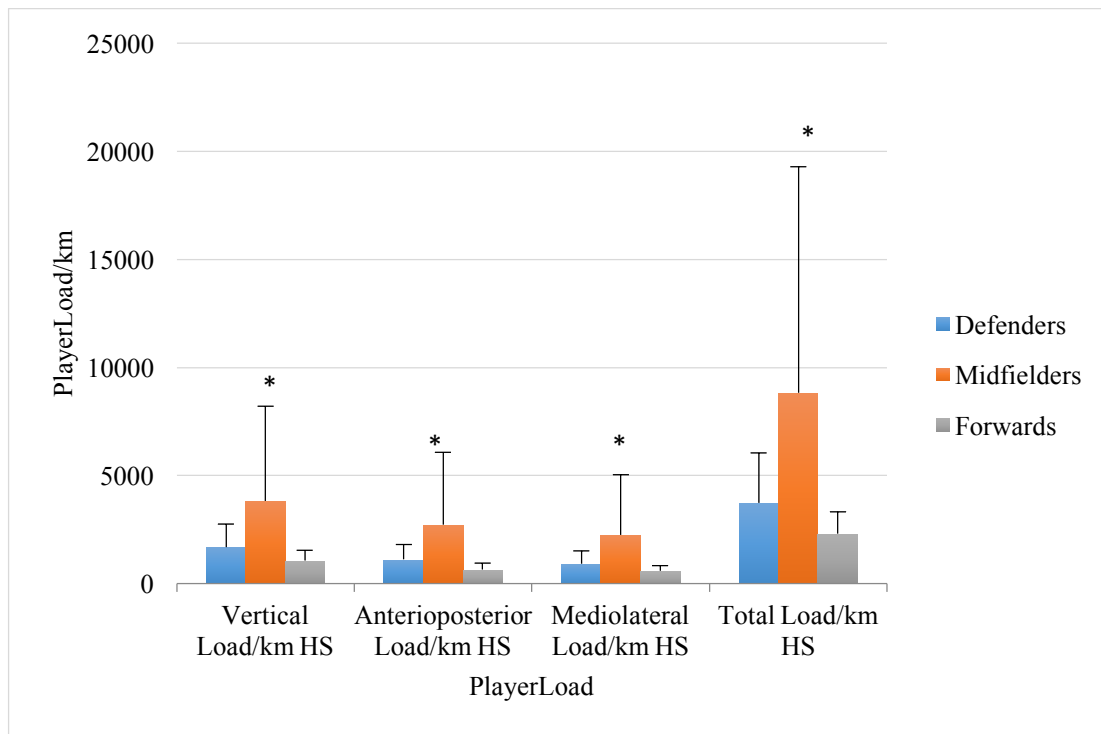


Figure 5.9. Total and uni-axial PlayerLoad per kilometer of high-speed distance ($5.5-11 \text{ m s}^{-1}$) of defenders, midfielders and forwards.

* denotes significantly different ($p < 0.05$) to other positions.

Figure 5.10 provides a summary of tri-axial PlayerLoad per kilometer of high-speed distance (km HSD: $5.5-11 \text{ m s}^{-1}$) covered during competitive matches for wide defenders, central defenders, midfielders, wide attackers and centre forwards. Midfielders had significantly greater vertical load per kilometer of high-speed distance ($3825 \pm 4383.9 \text{ AU/km HSD}$) than wide defenders ($1105.8 \pm 379.2 \text{ AU/km HSD}$, $p < 0.001$, $\text{ES}=1.1$, $95\% \text{ CI}=793.4 \text{ to } 4665$), central defenders ($2194.4 \pm 1227.6 \text{ AU/km HSD}$, $p=0.010$, $\text{ES}=0.7$, $95\% \text{ CI}=-117.5 \text{ to } 3398.7$), wide attackers ($1156.0 \pm 669.0 \text{ AU/km HSD}$, $p=0.001$, $\text{ES}=1$, $95\% \text{ CI}=439.8 \text{ to } 4819.2$) and centre forwards ($1002.6 \pm 323.2 \text{ AU/km HSD}$, $p < 0.001$, $\text{ES}=1.1$, $95\% \text{ CI}=898.2 \text{ to } 4766.7$). Midfielders had significantly greater antero-posterior load per kilometer of high-speed distance ($2717.1 \pm 3354.3 \text{ AU/km HSD}$) than wide defenders ($808.0 \pm 370.8 \text{ AU/km HSD}$, $p < 0.001$, $\text{ES}=1$, $95\% \text{ CI } 425.2 \text{ to } 3393$), central defenders ($1410.2 \pm 784.1 \text{ AU/km HSD}$, $p=0.007$, $\text{ES}=0.7$, $95\% \text{ CI}=-23.4 \text{ to } 2637.2$), wide attackers ($762.8 \pm 370.7 \text{ AU/km HSD}$,

$p=0.001$, ES=1, 95% CI=246.4 to 3662.3) and centre forwards (588.8 ± 212.2 AU/km HSD, $p<0.001$, ES=1.1, 95% CI=649.2 to 3607.6). Midfielders recorded significantly greater medio-lateral load per kilometer of high-speed distance (2261.3 ± 2771.1 AU/km HSD) than wide defenders (607.9 ± 206.1 AU/km HSD, $p<0.001$, ES=0.8, 95% CI=430.7 to 2876.2), central defenders (1204.4 ± 687.8 AU/km HSD, $p=0.008$, ES=0.5, 95% CI=-45.7 to 2159.5), wide attackers (687.6 ± 328.6 AU/km HSD, $p=0.001$, ES=0.7, 95% CI=162 to 2985.4) and centre forwards (525.6 ± 159.4 AU/km HSD, $p<0.001$, ES=0.8, 95% CI=525 to 2957.4). Midfielders recorded significantly greater tri-axial PlayerLoad per kilometer of high-speed distance (8821.0 ± 10469.6 AU/km HSD) than wide defenders (2521.8 ± 898.0 AU/km HSD, $p<0.001$, ES=0.8, 95% CI=1641.2 to 10957.2), central defenders (4808.8 ± 2644.9 AU/km HSD, $p=0.008$, ES=0.5, 95% CI=-188 to 8212.3), wide attackers (2606.4 ± 1363.7 AU/km HSD, $p=0.001$, ES=0.8, 95% CI=836.1 to 11593) and centre forwards (2116.6 ± 676.1 AU/km HSD, $p<0.001$, ES=0.8, 95% CI=2052 to 11356.8).

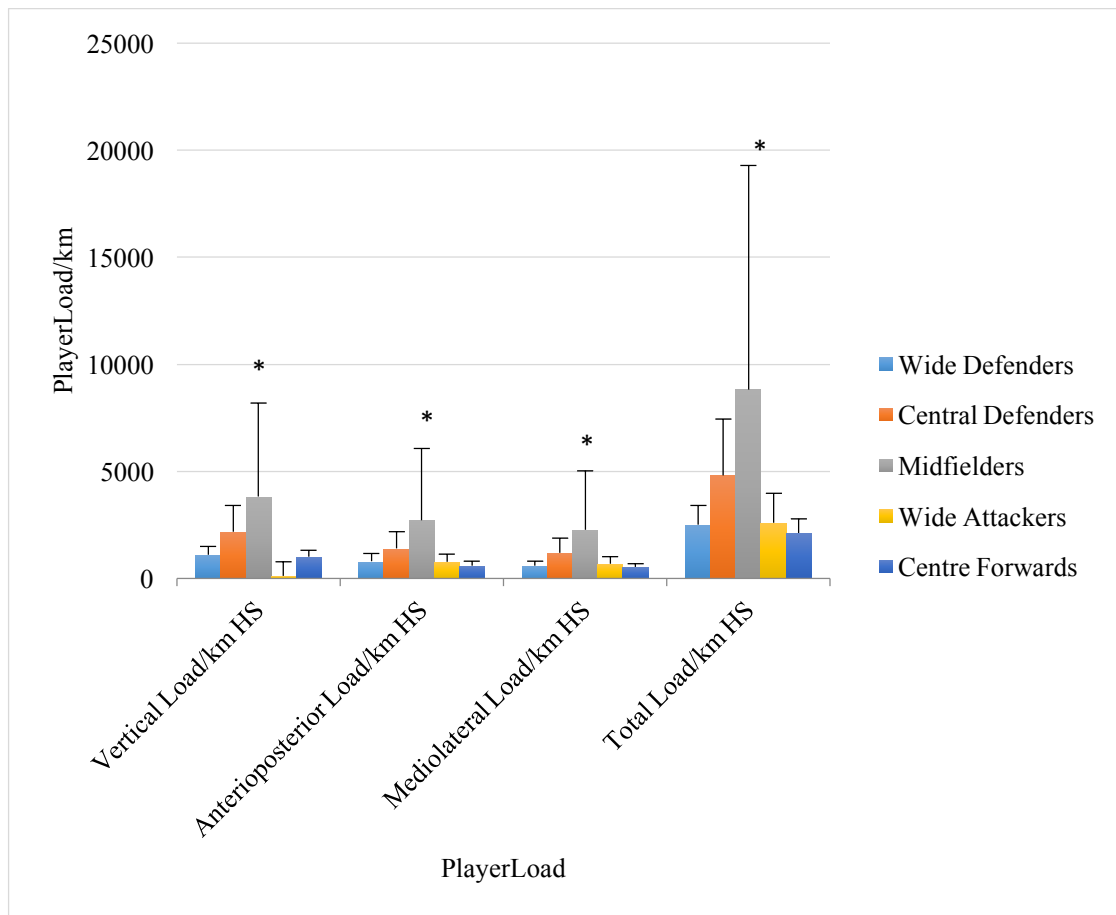


Figure 5.10. Total and uni-axial PlayerLoad per kilometer of high-speed distance ($5.5\text{-}11 \text{ m}\cdot\text{s}^{-1}$) of wide defenders, central defenders, midfielders, wide attackers and centre forwards.

* denotes significantly different ($p < 0.05$) to other positions.

Figure 5.11 provides a summary of tri-axial PlayerLoad contribution ratio of defenders, midfielders and forwards. Forwards recorded significantly greater medio-lateral load contribution ($25.7 \pm 1.7 \%$) than defenders ($24.6 \pm 1.7 \%$, $p = 0.006$, $ES = 0.6$, $95\% \text{ CI} = 0.3$ to 1.8) and midfielders ($24.8 \pm 1.6 \%$, $p = 0.042$, $ES = 0.5$, $95\% \text{ CI} = 0.0$ to 1.7). Forwards exhibited significantly less antero-posterior load contribution ($28.4 \pm 3 \%$) than defenders ($30.3 \pm 4.7 \%$, $p = 0.025$, $ES = 0.5$, $95\% \text{ CI} = -3.7$ to -0.2).

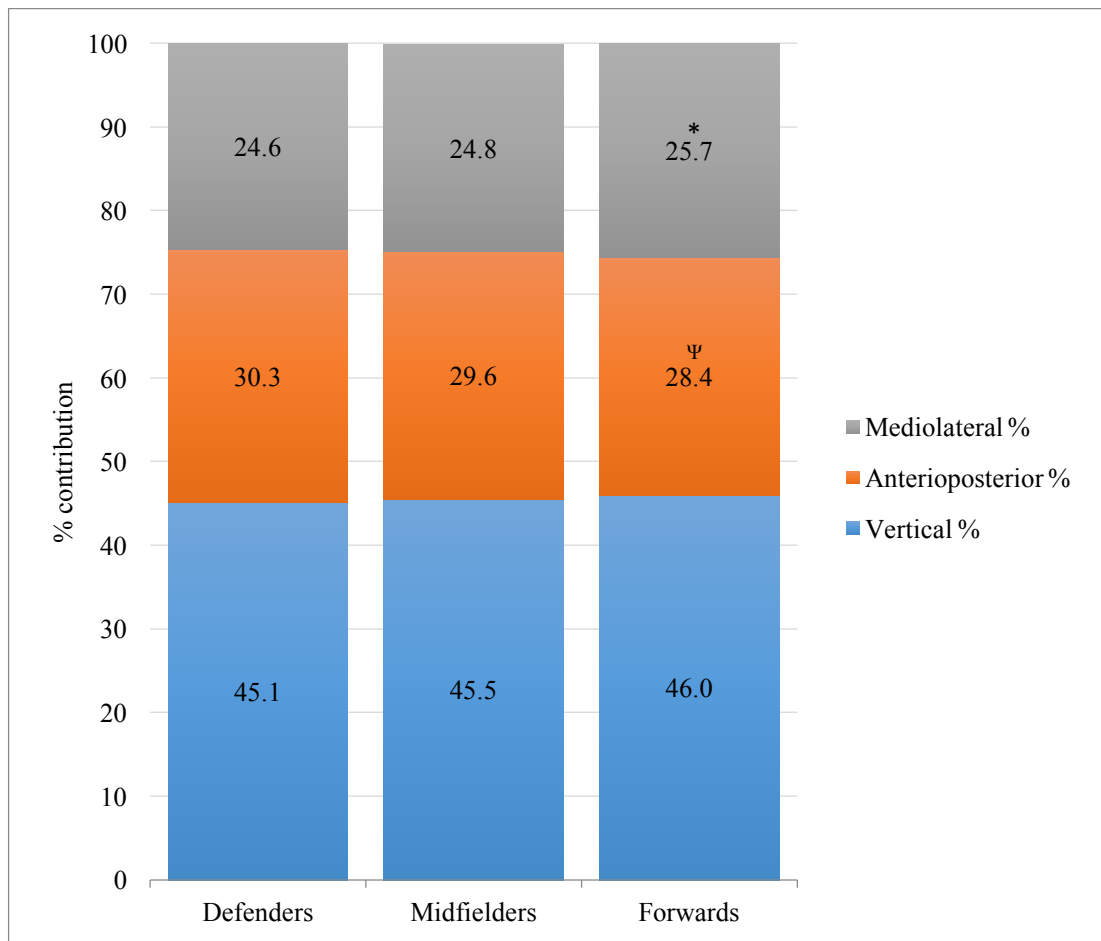


Figure 5.11. Uni-axial PlayerLoad contribution ratio of defenders, midfielders and forwards.

* denotes significantly different ($p < 0.05$) to all positions.

Ψ denoted significantly different ($p < 0.05$) to defenders.

Figure 5.12 provides a summary of tri-axial PlayerLoad contribution ratio of wide defenders, central defenders, midfielders, wide attackers and centre forwards. For vertical load contribution, centre forwards recorded a significantly greater percentage (47.4 ± 3.1 %) than wide defenders (44.3 ± 3.7 %, $p = 0.003$, $ES = 0.8$, $95\% CI = 1$ to 5.2) and wide attackers (43.7 ± 2.1 %, $p = 0.002$, $ES = 1.1$, $95\% CI = 1.9$ to 5.5). Centre forwards had a significantly less antero-posterior percentage load contribution (27.6 ± 3.3 %) than wide defenders (31.4 ± 4.8 %, $p = 0.001$, $ES = 0.8$, $95\% CI = -6.3$ to -1.2). Wide attackers had a significantly greater percentage contribution of medio-lateral load (26.8 ± 1.3 %) than wide defenders (24.3 ± 1.8 %, $p < 0.001$, $ES = 1.2$, $95\% CI = 2.3$ to 4.4), central defenders (24.9 ± 1.7 %, $p = 0.001$, $ES = 1.1$, $95\% CI = 1.8$

to 3.7), midfielders (24.8 ± 1.6 %, $p < 0.001$, ES=1.2, 95% CI=1.9 to 3.8) and centre forwards (25 ± 1.5 %, $p = 0.002$, ES=1.1, 95% CI=1.7 to 3.6).

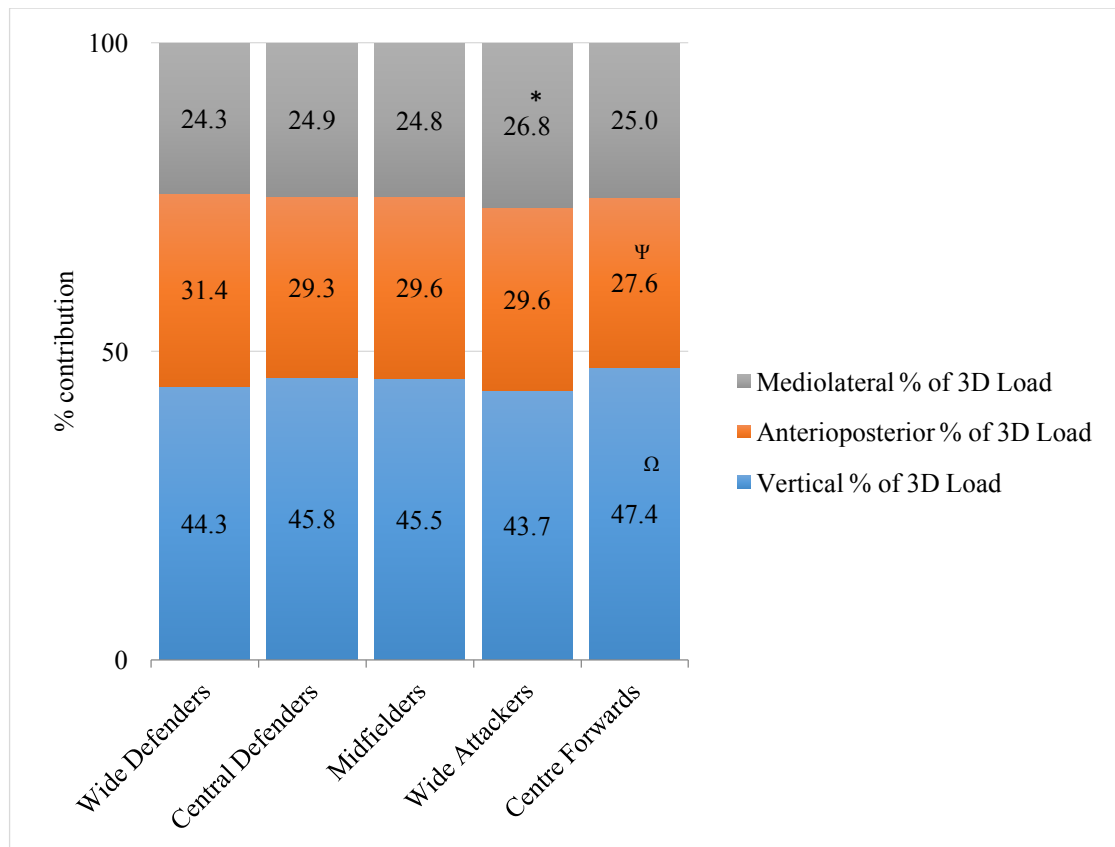


Figure 5.12. Uni-axial PlayerLoad contribution ratio of wide defenders, central defenders, midfielders, wide attackers and centre forwards.

* denotes significantly different ($p < 0.05$) to wide defenders.

Ψ denoted significantly different ($p < 0.05$) to defenders.

Ω denotes significantly different ($p < 0.05$) wide defenders and wide attackers.

5.4 Discussion

The present study aimed to quantify the work-rate profiles of elite level academy soccer players according to their positional role. The results show that forwards (9.78 ± 1.04 km) in the primary analysis and centre forwards in the secondary analysis covered the greatest distance during matches (9.94 ± 1.15 km). These findings are markedly different to previous studies

where midfielders covered a significantly greater distance than defensive and attacking players (Bradley et al., 2010; Dellal et al., 2011b; Dellal et al., 2010b; Di Salvo et al., 2007; Vigne et al., 2013; Wehbe, Hartwig and Duncan, 2013). Defenders covered the least distance over the course of games, a result that is in line with previous studies (Bradley et al., 2010; Buchheit et al., 2010a; Dellal et al., 2011b; Di Salvo et al., 2007). Differences between studies are most likely attributable to differences in tactics and positional remits within the team formation.

The observation of increased distance covered by forward players is explained with further analysis of the speed zones. Analysis of high-speed distance revealed centre forwards produced the greatest values (628.64 ± 161.15 m). These values are higher than the 487 ± 202 m reported by Akenhead *et al.* (2013) at velocities $>5.5 \text{ m.s}^{-1}$, and the 505 ± 209 m at velocities $>5.8 \text{ m.s}^{-1}$ reported by Russell *et al.* (2015). Direct comparisons are limited between studies based on methodological differences, but the higher distance covered by forwards at higher speeds is indicative of a tactical remit. Similarly, the differential between central and wide defenders highlights the influence of playing formation and tactics, and the importance in sensitivity of positional categorisation. Wide defenders covered a greater high-speed distance than midfielders, with implications for the development of position-specific training. In the previous chapters a squad mean score is presented, which negates the opportunity to investigate positional sensitivities.

The mean total distance covered across all positions (9.33 ± 0.97 km) is similar to the range presented previously for elite U18-U21 professional soccer players (Buchheit et al., 2010a; Pereira Da Silva, Kirkendall and Leite De Barros Netto, 2007; Russell et al; 2015). This value, based on seventeen competitive matches, is also comparable with the average produced across eight games in Chapter four (9.23 ± 1.02 km). There was a slight decrement in mean total distance covered in this study between the first and second half of the competitive matches, supporting previous literature (Andrzejewski et al., 2012; Bradley et al., 2011; Carling et al.,

2008; Rampinini et al., 2009). Previous studies have reported decrements in performance when comparing the first and second halves in the range of 1% to 5% (Bangsbo, Nørregaard and Thorsø, 1991; Carling et al., 2008; Hennig and Briehle, 2000; Mohr, Krstrup and Bangsbo, 2003;), whereas. Di Salvo *et al.*, (2007) found no difference between halves. In this study decrement of performance ranged from 1.8% to 8.2% in line with previous studies examining performance of elite level soccer players. The exception in the present study was wide defenders, who increased distance covered in the second half by 0.5%, although total distance was lower for defenders (Barros et al; 2007; Burgess, Naughton and Norton, 2006). The nature of the sport elicits fatigue that causes a decline in the capacity to sustain muscular work made evident towards the end of the game (Mohr, Krstrup and Bangsbo, 2003). This performance limitation factor requires both the comprehension of the energy and mechanical demands in football to aid in the understanding of movement patterns in football (Bangsbo, Mohr and Krstrup, 2006; Osgnach et al., 2010). Over the course of a 90-minute game, players change activity on average every 5 seconds and perform approximately 1300 actions, with 200 of these being completed at high intensity (Mohr, Krstrup and Bangsbo, 2003). The mechanical load that players endure span beyond running and include changes of direction, dribbling, tackling and heading, all of which require high level of force production (Rampinini, et al., 2011). Furthermore, the data findings could be a result of pacing strategies that have been implemented in Australian Football and soccer as a method of coping with fatigue (Couts et al., 2010; Duffield, Coutts, and Quinn, 2009; Rampinini et al., 2007b; Mohr, Krstrup and Bangsbo, 2003; Bradley et al., 2009). In this study defenders showed the least decrement while forwards (primary analysis) and centre forwards (secondary analysis) had the greatest decrement in performance. This could be a result of the more explosive movements performed by the attacking players during match play, and again highlights the importance of positional categorisation.

With reference to PlayerLoad, the highest values exhibited by midfielders followed by forwards and defenders is in agreement with previous research (Barron et al., 2014). Midfielders accumulated significantly greater PlayerLoad in all movement planes, although there was a similar directional contribution across all movement planes and positions in the primary analysis. The greater PlayerLoad exhibited by midfielders might be indicative of greater frequency and/or magnitude in acceleration. Secondary analysis of positional loading highlighted that wide attackers exhibited significantly greater medio-lateral contribution to total load. This is indicative of greater lateral movement, potentially both with and without the ball. Conversely, central attackers exhibited greater vertical load, potentially as a result of more heading duels, and a compensatory decrease in antero-posterior contributions to loading. This would suggest that the forwards in this formation do not play in straight lines, but rather complete a high level of fast, multi-directional movements. The highest load observed in midfielders may be another indicator of game requirements, linking defenders and attackers. Defenders recorded significantly less medio-lateral load than midfielders and forwards, and the interaction of the various positions will have implications for the biomechanical demands. Whilst these positional remits are designed around technical and tactical remits, the physical implications might inform the development of position-specific physical training programmes. This sensitivity in analysis highlights a potential merit in tri-axial accelerometry.

Secondary analysis across five playing positions revealed that wide attackers (or wingers) shared a similar movement pattern to their defensive counterparts. Therefore, the secondary analysis was successful in providing a precise movement profile that revealed that within the sub-categories of defenders (wide and central) and forwards (wide attackers and centre) there are significant differences to midfielders. This might suggest player groupings based on wide vs central rather than defender vs midfielder vs central. The training implications for the club are large as it is clear that intra-group differences exist within playing positions. Midfielders

generated significantly different total PlayerLoad to all positions except wide attackers. It can be inferred that wide attackers tend to possess the same movement profile to midfielders since they share the same duties of linking play to the forwards.

The relationship between PlayerLoad and distance covered revealed that correlations were also position-specific, with forwards exhibiting the strongest correlations. This interaction between PlayerLoad and distance covered has been examined previously, and the highly intermittent and multi-directional nature of forward play, along with the emphasis on high-speed entries, promotes the accumulation of PlayerLoad.

5.5 Conclusion

In the literature it has been well documented that midfielders cover the greatest distance due to their positional demands of linking play between defenders and attackers (Di Salvo et al., 2007). In addition, midfielders are considered the fittest players on the squad (Hoff et al., 2002). However, soccer is a self-paced sport, such that physical capacity will not necessarily dictate distance covered. In this study, and not generalisable beyond this team, the attackers covered greater (total and high-speed) distance than defenders and midfielders. Midfielders exhibited the greatest PlayerLoad across all three movement planes, with implications for training programme design. Furthermore, the categorisation of playing position is critical in understanding the influence of playing position. A traditional unit categorisation of defenders, midfielders and forwards negates important sensitivities in the influence of width on physical demands.

The significant differences across playing positions recorded in this study have implications for training and recovery. The thesis has already examined the differences among training and match data along with the differences in performance in relation to age. With this in mind it is

evident that training could benefit from position-specific drills that can address the differences that exist as presented in this chapter.

CHAPTER 6. The influence of fatigue on indices of PlayerLoad

6.1 Introduction

The previous studies have developed the measure of PlayerLoad to assess the efficacy of training drills to replicate the physical demands of match play, and the influence of playing age and position on those demands. In the previous chapters the match has been sub-divided into each half, with data suggesting a difference in performance criteria between each half. This temporal pattern is mirrored in epidemiological observations of injury incidence, with more injuries incurred during the 2nd half of matches (Ekstrand et al., 2011a; Hawkins et al., 2001). Further analysis of the primary types of injury, i.e muscular strains and ligamentous sprains, suggests a greatest risk of injury during the final 15mins of match play (Ekstrand et al., 2011a; Woods et al., 2003) indicative of a fatigue effect. The tri-axial nature and high sampling frequency of GPS-based accelerometry might be further developed to consider injury risk in addition to markers of performance. The full potential of GPS athlete monitoring system has not been fully explored from an injury prevention perspective (Colby, et al., 2014).

The PlayerLoad (Catapult Innovations, Melbourne, Australia) variable quantifies the mechanical strain imposed on the body during movement. It is calculated as the square root summation of antero-posterior, medio-lateral and vertical accelerations and presented as arbitrary units (AU):

$$\text{PlayerLoad} = \sqrt{\frac{((\text{fwd}_{t=i+1} - \text{fwd}_{t=i})^2 + (\text{side}_{t=i+1} - \text{side}_{t=i})^2 + (\text{up}_{t=i+1} - \text{up}_{t=i})^2)}{100}}$$

This formula quantifies the instantaneous rate of change in acceleration (Boyd, Ball, and Aughey, 2011). However, without the magnitude of acceleration being calculated the values of PlayerLoad may not properly quantify the true value of mechanical strain the soccer players,

in this case, experience. Considering only the change in acceleration, and not the magnitude of acceleration, means that a player would exhibit the same load when changing by 0.1 m s^{-2} either at walking pace or sprinting. Intuitively PlayerLoad would be higher at the greater speeds, but this is not considered in this calculation. Figure 6.1 summarises the calculation of instantaneous change in acceleration, which negates the area under the acceleration-time curve.

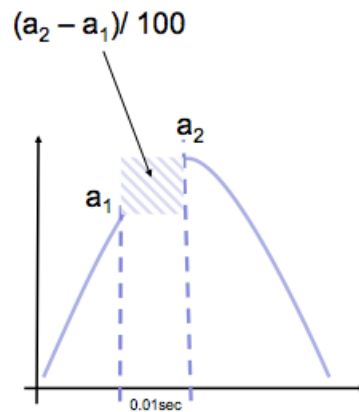


Figure 6.1. Graphical representation of PlayerLoad formula.

In order for sport scientists to obtain representative values of PlayerLoad it is proposed that the area under the curve (*iLoad*) be included in the calculation, analogous to the use of iEMG in electromyographical research. In an electromyogram the iEMG parameter is a marker of both magnitude and duration of the response, and the integral of the curve a marker of total work done. This formula would quantify the area under the acceleration-time curve (Figure 6.2).

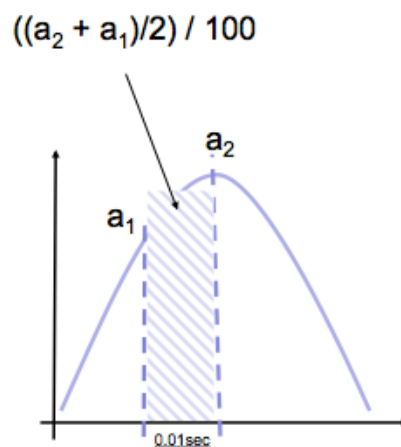


Figure 6.2. The calculation of *iLoad*.

An additional mechanical constraint of the calculation of load is in the treatment of each vector. The acceleration in each plane is squared, and then square rooted, which removes any negative values. However, the distinction between positive and negative values is fundamental to a greater understanding of movement quality, with implications for both performance and injury risk. In the medio-lateral plane, for example, negative values represent medial displacement, and positive relates to lateral movement. Asymmetry in the medial and lateral load would have clear implications for movement patterning, and potentially injury risk. Similarly, in the antero-posterior plane the sign convention differentiates between backward and forward movement.

A third mechanical critique of the calculation of PlayerLoad is in the additive nature of load, where the sum of accelerations in x, y, z does not equate to the value output for total load. In the previous chapters each directional vector has been considered separately, such that the total load is a cumulative value. This is markedly different to the software output of total load, where the distinction is between $\sqrt{x^2 + y^2 + z^2}$ as recommended by the manufacturer and $(\sqrt{x^2} + \sqrt{y^2} + \sqrt{z^2})$ as used in this thesis. Previous chapters have highlighted the sensitivity in considering each vector as a separate parameter, since total '3D' load could be attained by infinite variations in x, y, z.

The aim of this study was to apply this novel quantification of PlayerLoad to match play data to investigate the influence of fatigue, regularly cited as a factor in both performance impairment and increased injury risk. The mechanical complexity associated with fatigue-induced changes in technique is considered appropriate for the increased mechanical rigour in the analysis of acceleration data. Proposing that the present formula (Boyd, Ball and Aughey, 2011) has fundamental biomechanical limitations, iLoad was developed in order to provide a biomechanically valid soccer player profile akin to force plate analysis.

6.2 Methodology

Participants

Analyses were performed over the course of one season (2011-2012). Over this period 112 datasets were collected from 32 male outfield players (age: 17.2 ± 0.7 years; height: 177 ± 6 cm; body mass: 73.2 ± 6.4 kg) who completed 90 min of competitive matches ($n=17$). Player consent and approval by the football club for the study were obtained. These data arose as a condition of employment in which player performance was routinely measured over the course of the competitive season (Winter and Maughan 2009). All match performance-related data were anonymised before analysis to ensure team and player confidentiality.

Procedures

Players were fitted with portable 10Hz GPS units (MinimaxX S4, Catapult Innovations, Canberra, ACT, Australia) worn in a custom-made garment between their shoulder blades. The measure of load collected was PlayerLoad, (which is a modified vector magnitude expressed as the square root of the sum of the squared instantaneous rates of change in acceleration in each of the 3 planes divided by 100), (Boyd, Ball and Aughey, 2011). Data was collated for 15-minute segments of each game (0-15 minutes, 15-30 minutes, 30-45 minutes, 45-60 minutes, 60-75 minutes, 75-90 minutes). Triaxial accelerometers (100Hz sampling frequency) are highly sophisticated motion sensors that measure the frequency, magnitude and orientation of body movement in three dimensions (Boyd, Ball and Aughey, 2013). PlayerLoad was distributed across the three acceleration planes of movement a_x , a_y , a_z . The accuracy and reliability of this technology is very high, providing measures that can objectively be assessed (Varley, Fairweather and Aughey, 2012). Examination of 10Hz and 15Hz GPS units revealed greater validity and reliability for the former (Johnston et al., 2014). Research on 10Hz GPS

units presented a mean error of 10.9 and 5.1 when analysing distances of 15 metre and 30 metre straight line running, respectively (Castellano et al., 2011). Comparison of 10Hz (MinimaxX S4, 10 Hz, Catapult Innovations) and 15Hz GPS (SPI-ProX, 15Hz, GPSports) units was carried out through the completion of a team sport simulation circuit completed by 8 trained male participants (Johnston et al., 2014). Actual total distance was not significantly different to the 10Hz unit ($p=0.149$). Actual peak speed ($22.47 \pm 2.64 \text{ km} \cdot \text{h}^{-1}$) revealed significant difference compared to 10Hz GPS unit ($22.98 \pm 2.08 \text{ km} \cdot \text{h}^{-1}$, $p = 0.01$). Interunit reliability for peak speed revealed 10Hz GPS (1.64%) were improved in comparison to previous research examining 1Hz and 5Hz GPS units (2.3-7.2%) (Barbero-Alvarez et al., 2010; Coutts and Duffield, 2010; Johnston et al., 2012). Across all movement demands examined 10Hz GPS units displayed lower levels of error (<14%) in contrast to 15Hz GPS units ($\leq 20\%$). The 10Hz GPS units possessed an improved ability to measure team sport movement demands in comparison to 1Hz and 5Hz units. In addition, 10Hz GPS units provide more valid and reliable feedback for training and match purposes (Johnston et al., 2014).

Statistical Procedures and Tests

Physical data was derived from Catapult Sprint software version 5.0 (Catapult Innovations, Canberra, ACT, Australia) and collated using Microsoft Excel. The raw PlayerLoad data was then processed through the new formula to produce magnitude of *i*Load in each direction of movement. Descriptive statistics for data were calculated and reported as means and standard deviations. A repeated measures analysis of variance (ANOVA) was employed to investigate differences in mean scores between *i*Load and the formula utilised in chapters four and five ($\sqrt{x^2} + \sqrt{y^2} + \sqrt{z^2}$). Measure of Cohen's d effect size and 95% confidence intervals were reported for the mean difference for pairwise comparisons. The relationships between PlayerLoad, *i*Load, total distance and speed zones

(0.2-2 m·s⁻¹, 2-4 m·s⁻¹, 4-5.5 m·s⁻¹, 5.5-11 m·s⁻¹) were assessed using the Pearson's correlation coefficient. Magnitude of correlation coefficients was considered as trivial ($r < 0.1$), small ($0.1 < r < 0.3$), moderate ($0.3 < r < 0.5$), large ($0.5 < r < 0.7$), very large ($0.7 < r < 0.9$), almost perfect ($r > 0.9$) or perfect ($r = 1$; Hopkins, 2002). All the statistical analyses were performed using SPSS 20 (IBM, 2013) for Mac OS (Apple Computer), with significance being set at $p \leq 0.05$.

6.3 Results

Figure 6.3 provides a summary of positive (+ve) and negative (-ve) medio-lateral (ax) load of six time segments during games using proposed *iLoad* calculation. Mean -ve ax (orientation to the left) was -119.6 ± 58.8 AU and +ve ax (orientation to the right) was 93.7 ± 45.3 AU. It was found that -ve ax was slightly larger than +ve ax, that indicates dominance, however there was no statistical main effect for time.

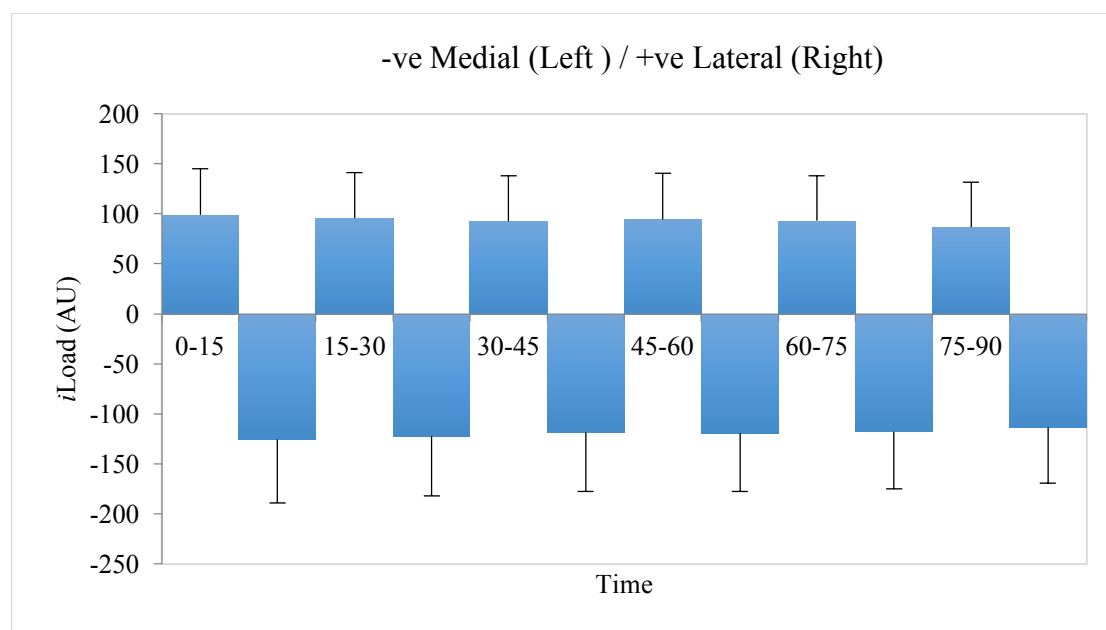


Figure 6.3. Medial and Lateral *iLoad* over 90-min match play.

Figure 6.4 presents the medio-lateral load recorded during matches across six time segments utilising the formula from chapter four and five ($\sqrt{x^2} + \sqrt{y^2} + \sqrt{z^2}$). During the first segment (0-15 minutes) medio-lateral load (22.6 ± 3.7 AU) was significantly greater to 30-45 minutes

(21.9 ± 3.4 AU, $p=0.008$, ES=0.19, 95% CI=-1.08-2.48), 60-75 minutes (21.1 ± 3.1 AU, $p=0.003$, ES=0.43, 95 % CI=-0.21-3.21) and 75-90 minutes (20.8 ± 3.3 AU, $p<0.001$, ES=0.5, 95% CI=0.05-3.55). Medio-lateral load recorded during 15-30 minutes was significantly greater than equivalent value during 75-90 minutes ($p=0.027$, ES=0.33, 95% CI=-0.55-2.75).

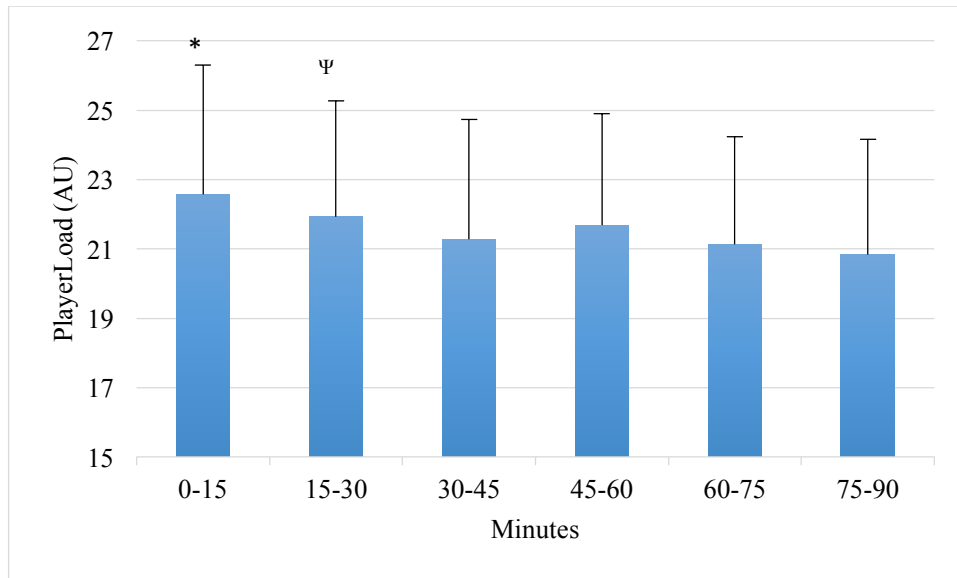


Figure 6.4. Medio-lateral PlayerLoad over 90-minute match play.

* significantly different to -ve fx 30-45, 60-75, 75-90.

Ψ significantly different to 75-90.

Figure 6.5 provides a summary of +ve (forward orientation) and -ve (backward orientation) antero-posterior (ay) load of six time segments during games using proposed *iLoad* calculation. Mean +ve ay was 470.38 ± 191.83 arbitrary units and mean -ve ay was -76.21 ± 177.83 arbitrary units. Majority of ay load is found to be in the forward direction however no statistical main effect for time was found amongst the six time segments.

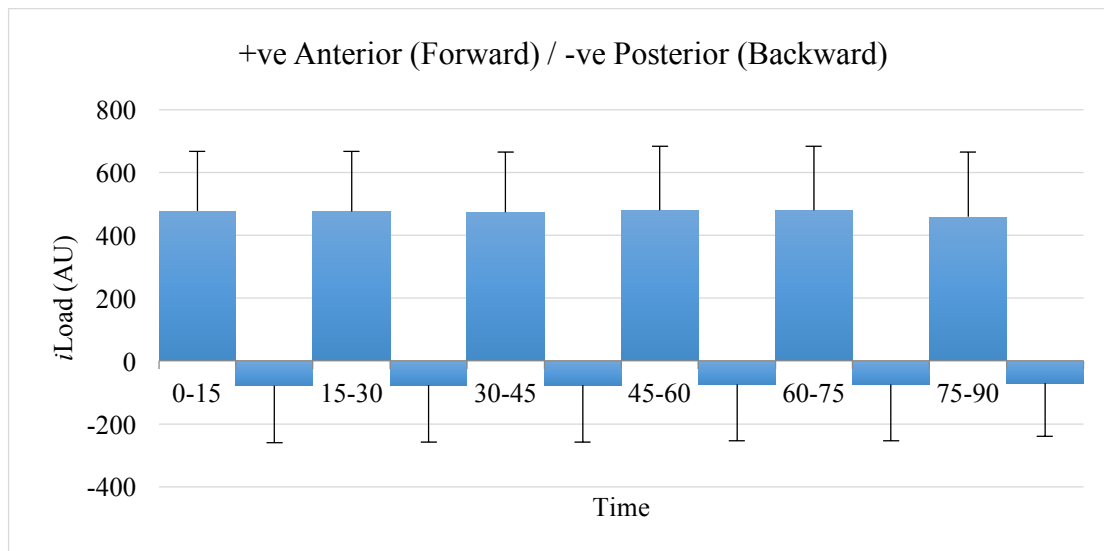


Figure 6.5. Anterior and Posterior *iLoad* over 90-minute match play.

The antero-posterior load of six time segments recorded during matches using the formula from chapter four and five ($\sqrt{x^2} + \sqrt{y^2} + \sqrt{z^2}$) is summarised in Figure 6.6. No significant main effect for time was found amongst the six time segments.

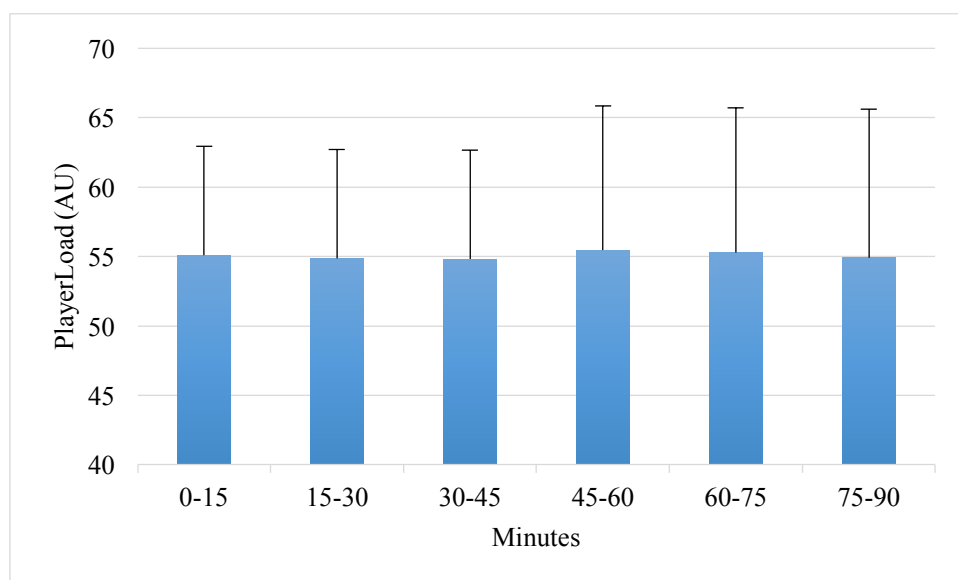


Figure 6.6. Antero-posterior PlayerLoad over 90-minute match play.

Figure 6.7 provides a summary of +ve (takeoff) and -ve (landing) vertical load (az) of six time segments during games using proposed *iLoad* calculation. Mean +ve az was 719.5 ± 67.13

arbitrary units and –ve az was -24.34 ± 8.17 arbitrary units. The majority of vertical movement is conducted in the +ve az. Statistical main effect for time was found in –ve az at 75-90 minutes in comparison to 15-30 minutes ($p=0.037$, ES=0.32, 95% CI=-1.87-5.45), 30-45 minutes ($p=0.018$, ES=0.32, 95% CI=-1.78-6.96) and 60-75 minutes ($p=0.015$, ES=0.30, 95% CI=-1.66-7.04).

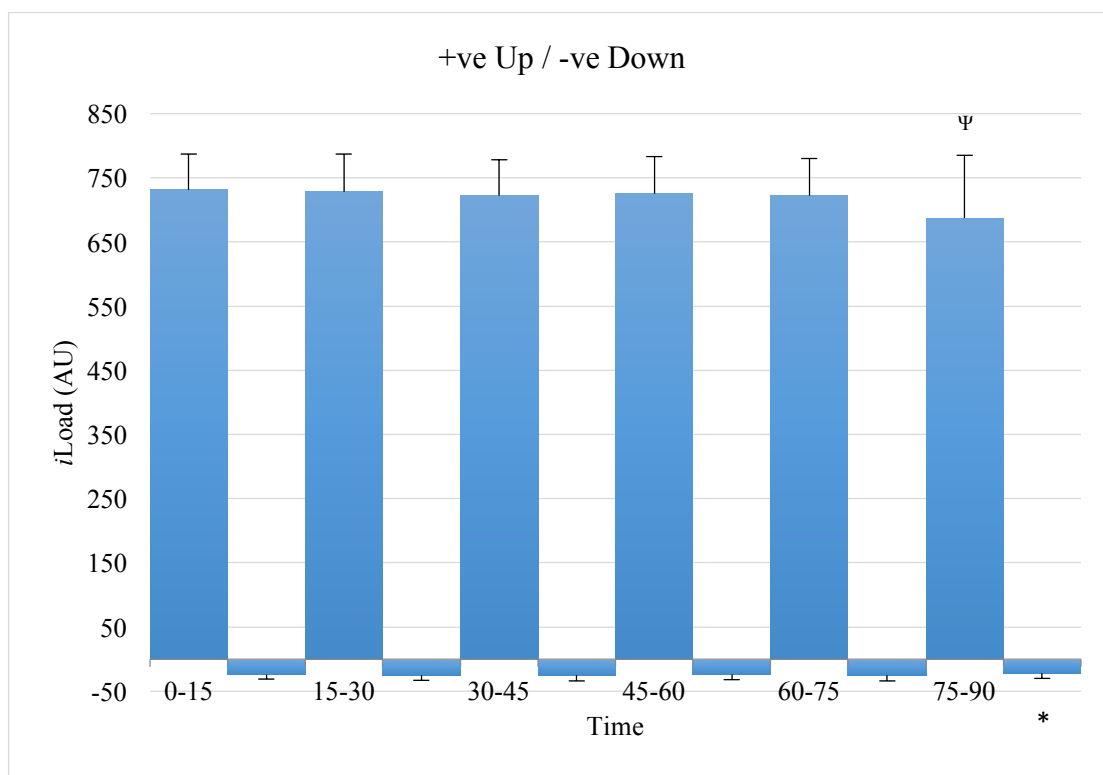


Figure 6.7. Vertical *i*Load over 90-minute match play.

* significantly different to –ve az 15-30, 30-45, 60-75.

Ψ significantly different to all +ve az during 90-minute match play.

Vertical load recorded during six time segments of 90-minute matches are presented in Figure 6.8 utilising the formula from chapter four and five ($\sqrt{x^2 + y^2} + \sqrt{y^2 + z^2}$). No significant main effect for time was found amongst the six time segments.

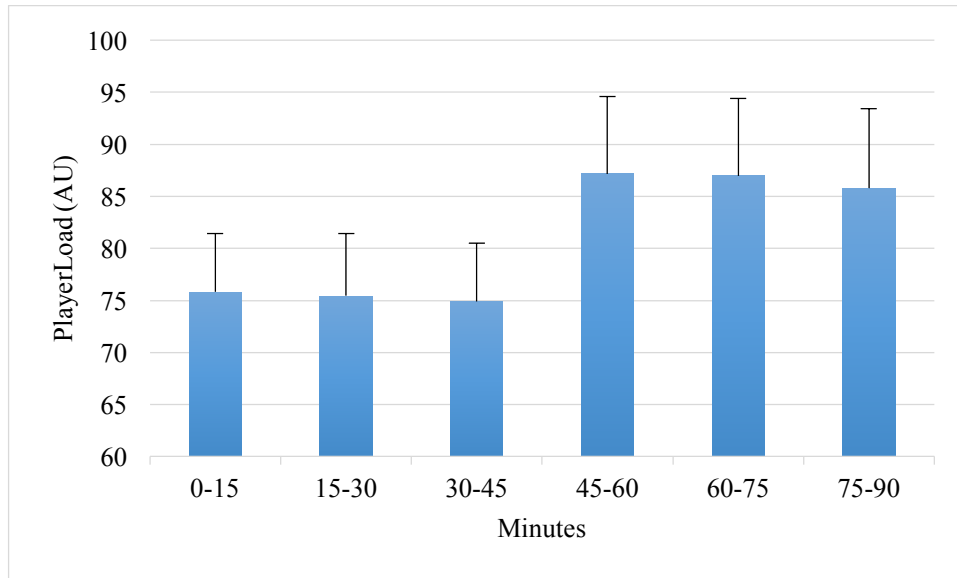


Figure 6.8. Vertical PlayerLoad over 90-minute match play.

Table 6.1 presents the correlation of PlayerLoad and *i*Load with distance covered in each 45-minute half of official match play.

Table 6.1. Linear correlation coefficient between PlayerLoad, *i*Load and distance.

PlayerLoad – Distance 1 st Half	PlayerLoad – Distance 2 nd Half	<i>i</i> Load - Distance 1 st Half	<i>i</i> Load – Distance 2 nd Half
$r=0.36$	$r=0.33$	$r=0.19$	$r=0.19$
$p<0.001$	$p<0.001$	$p=0.05$	$p=0.04$

Table 6.2 summarises the correlation between PlayerLoad and *i*Load for total tri-axial and each directional uni-axial plane during six 15-minute intervals (0-15, 15-30, 30-45, 45-60, 60-75, 75-90) of official match play.

Tables 6.3 and 6.4 summarise the relationship between both PlayerLoad and *i*Load with distance covered over four speed zones (0.2-2 m·s⁻¹, 2-4 m·s⁻¹, 4-5.5 m·s⁻¹, 5.5-11 m·s⁻¹).

Table 6.2. Linear correlation coefficient between PlayerLoad and *i*Load during match play.

	Total	Medio- Lateral	Anterio- Posterior	Vertical
0 – 15 min	$r=0.17,$ $p=0.08$	$r=0.35,$ $p=0.01$	$r=0.07,$ $p=0.45$	$r=0.11,$ $p=0.24$
15-30 min	$r=0.15,$ $p=0.13$	$r=0.27,$ $p=0.01$	$r=0.05,$ $p=0.58$	$r=0.09,$ $p=0.36$
30 – 45 min	$r=0.05,$ $p=0.62$	$r=0.18,$ $p=0.08$	$r=0.01,$ $p=0.92$	$r=0.05,$ $p=0.59$
45 – 60 min	$r=0.02,$ $p=0.88$	$r=0.25,$ $p=0.01$	$r=0.07,$ $p=0.45$	$r=0.07,$ $p=0.47$
60 – 75 min	$r=0.02,$ $p=0.81$	$r=0.19,$ $p=0.05$	$r=0.09,$ $p=0.31$	$r=0.02,$ $p=0.81$
75 – 90 min	$r=0.03,$ $p=0.79$	$r=0.14,$ $p=0.15$	$r=0.07,$ $p=0.47$	$r=0.03,$ $p=0.79$

Table 6.3. Linear correlation coefficient between PlayerLoad and distance covered in each of the four speed zones.

0.0 - 2.0 m·s ⁻¹	2.0 – 4.0 m·s ⁻¹	4.0 - 5.5 m·s ⁻¹	5.5 - 11.0 m·s ⁻¹
$r=0.23,$ $p=0.01$	$r=0.29,$ $p=0.002$	$r=0.13,$ $p=0.17$	$r=-0.19,$ $p=0.47$

Table 6.4. Linear correlation coefficient between *i*Load and distance covered in each of the four speed zones.

0.0 - 2.0 m·s ⁻¹	2.0 – 4.0 m·s ⁻¹	4.0 - 5.5 m·s ⁻¹	5.5 - 11.0 m·s ⁻¹
$r=-0.78,$ $p=0.41$	$r=-0.13,$ $p=0.16$	$r=0.30,$ $p=0.001$	$r=-0.09,$ $p=0.37$

6.4 Discussion

This chapter considers a novel interpretation of PlayerLoad that considers the magnitude of acceleration in addition to the instantaneous change in acceleration. By quantifying the area under the acceleration-time curve, an integrated value of PlayerLoad is achieved, here termed *i*Load using the EMG analogy. The consideration of sign convention also enables a more detailed analysis of movement by differentiating, for example, between medial and lateral load as opposed to a gross medio-lateral value. This data was obtained during match play to consider the temporal pattern of change.

The sign convention would enable an evaluation of movement symmetry. The data highlights a 1.3:1 ratio on medial:lateral load, suggesting greater magnitude of acceleration to the medial, left side. In a context as complex as match play this interpretation is difficult, however the predominance of right footed players would typically cut to the left. In the antero-posterior plane the consideration of *i*Load revealed a 6.2:1 ratio on forward:backward running, clearly interpreted as greater contribution from running in the forward direction. In the vertical plane the ratio was 29.6:1 in favour of upward movement. Movement across the vertical plane presented interesting findings concerning distribution of actions during 90 minutes. The vertical takeoff forces clearly dominate the equivalent landing forces. With the decrease of a_z (+ve a_z 60-75 min: 722.67, 75-90 min 687.41; -ve a_z 60-75 min: -25.28, 75-90 min: 22.61) in both directions in the last 15 minutes of the match it is reasonable to consider the presence of fatigue. The landing forces during 75-90 minutes are significantly different to the values in the earlier periods of the matches (15-30 minutes, $p=0.037$, $ES=0.32$, 95% $CI=-1.87-5.45$, 30-45 minutes, $p=0.018$, $ES=0.32$, 95% $CI=-1.78-6.96$ and 60-75 minutes, $p=0.015$, $ES=0.30$, 95% $CI=-1.66-7.04$). This decrease in a_z is indicative of fatigue since it is the dominant plane of movement as seen in the other studies of this PhD thesis.

Medio-lateral PlayerLoad was also found to be significantly higher during the first 15 minutes of match play (0-15 minutes) in comparison to the latter stages of the game (30-45 minutes, $p=0.008$, $ES=0.19$, 95% $CI=-1.08-2.48$, 60-75 minutes, $p=0.003$, $ES=0.43$, 95 % $CI=-0.21-3.21$ and 75-90 minutes $p<0.001$, $ES=0.5$, 95% $CI=0.05-3.55$) while *i*Load exhibited a non-significant decrease for the same time period in both medial and lateral directions (left and right). Load is based on the instantaneous change in magnitude, and so more frequent changes in acceleration would create a higher load. A lower *i*Load would suggest less magnitude in acceleration. Similarly, the increase in vertical PlayerLoad in the 2nd half is not consistent with the observations of *i*Load in +ve and -ve z.

The fundamental difference in the calculation of PlayerLoad based on the rate of change in acceleration with or without a consideration of magnitude is highlighted in the lack of correlation between the parameters. The highest r value observed at 0.35 would still only explain 12% of variance. In this respect the two parameters must be considered discrete. PlayerLoad was observed to have a stronger correlation with distance covered (1st half $r=0.36$, $p<0.001$, 2nd half $r=0.33$, $p<0.001$) than *i*Load (1st half $r=0.19$, $p=0.05$, 2nd half $r=0.19$, $p=0.04$). These findings did not support previous research (Casamichana and Castellano, 2015) of the correlation between PlayerLoad and total distance ($r=0.75$, $p<0.001$). The lack of correlation between distance covered and PlayerLoad was consistent across all four speed zones (0.2-2 m·s⁻¹, 2-4 m·s⁻¹, 4-5.5 m·s⁻¹, 5.5-11 m·s⁻¹), supporting previous chapters. However, *i*Load exhibited a strong correlation ($r = 0.78$) with distance covered in the lowest speed zone. Here the magnitude of acceleration change is likely to be lower, and velocity more constant. In this case distance travelled at these speeds will accrue a relatively linear increase in *i*Load.

The innovation in the soccer mechanics of this study lies in the orientation of movement. Research has concluded that more ankle injuries occur on the dominant side as opposed to the

non-dominant side (Woods et al., 2003). Therefore, with the establishment of dominant side of movement through the use of *iLoad*, there is opportunity for future investigation in dominant and non-dominant loading profiles of soccer players.

Future studies can examine position differences based on this formula. In addition, this study sets the foundation of development into an investigation of movement quality. Such studies may aid in underlining the correlation of load and injury, an area that has not been examined in previous studies with the PlayerLoad variable. There is potential of carrying out analyses across various playing positions with this new formula, similarly to the methodology adopted in chapter five of the thesis.

6.5 Conclusion

The findings in this novel study provide evidence of the representative magnitude of load that soccer players experience during competitive match play. Anterio-posterior and medio-lateral load did not reveal any significant differences during match periods. The clear dominance in forward movement and slight favor of left movement in comparison to backward movement and to the right provides sport scientists with necessary information when designing movement mechanics drills. Vertical *iLoad* both takeoff and landing exhibited significant differences over the course of 90-minute matches. This decrease in load can be an indicator of fatigue since anterio-posterior and medio-lateral load is sustained at the same level during competitive matches. Correlations between *iLoad* and PlayerLoad were small to trivial and this could be potentially attributed to the novel formula (*iLoad*) measuring magnitude of change in acceleration while PlayerLoad measures frequency of change in acceleration – fundamentally different concepts. Thus, *iLoad* can provide a measurement of magnitude of acceleration that potentially creates a representative value of the forces produced by soccer players during match play. By adopting principles analogous to kinetic analyses in force platform and

electromyography, additional analysis parameters may be defined which provide greater depth of information in movement quality. The implications in movement asymmetry also have implications for the monitoring of injury risk.

CHAPTER 7. Summary

The central aim of this thesis was to investigate the use of portable GPS technology to measure biomechanical intensity in elite level soccer. Specifically, the studies provide the analysis of physical and mechanical data to examine (a) the specificity of training drills in comparison to 90-minute matches, (b) the ability of uni-axial PlayerLoad to identify changes by player with relation to age (U16, U18, U21) and position, (c) a critical examination of the PlayerLoad calculation to examine the influence of fatigue during match play. The final chapter will attempt to integrate the experimental studies presented in this thesis to consider the potential highlighted by Chambers (2015) involving the ability of GPS technology to precisely detect sport-specific movements in soccer.

Approaching the Premier League soccer academy for the purpose of conducting this PhD research was an opportunity to evaluate performance monitoring of youth players. The Technical Director implemented a new soccer training programme for the youth players and GPS technology allowed for performance during training and matches to be analysed in order to evaluate the outlined plan. Therefore, this PhD research project took a current practice in an elite environment that incorporates GPS technology within the profiling of player activity and developed this application to explore the scope of analysis and focus on the mechanical intensity of performance.

7.1 Small-sided games implemented in training sessions

The training drills implemented at the academy were assessed on the basis of the specificity in relation to match play, utilising gross GPS measures including distance covered and PlayerLoadTM. Training data included possession drills, movement patterns, game related drills and small-sided games. The later was chosen as research has shown that the implementation of

small-sided games into training sessions can help soccer players develop the endurance capacity required for match play (Mallo and Navarro, 2008). This rationale based on a physiological validity of small-sided games has typically failed to consider the biomechanical response and validity of the activity profile. An intuitive relationship should not be assumed. In attempting to replicate the demands of match play using small-sided games an analogy can be drawn in the development of laboratory-based protocols to replicate the ‘physical’ demands of match play. The term ‘physical’ has been used to encompass the physiological and biomechanical response. However, this pursuit has typically failed to achieve validity in both domains. Early examples of free-running (Nicholas, Nuttall and Williams, 2000) and treadmill-based (Drust, Reilly and Cable, 2000) protocols claimed to validate the physiological response to match play. However, examination of the activity profile suggests that the biomechanical demands imposed by the intermittent nature of soccer are not validly modelled. Subsequent attempts to more closely replicate the high frequency of speed change and provide a valid biomechanical stress (Greig, McNaughton and Lovell, 2006) failed to produce a valid physiological response based on match play. This dichotomy highlights the complex interaction of physiological and biomechanical demands, and a validation of small-sided games to date has been restricted to their physiological stress.

Study one explored the training programme implemented at the academy (various forms of training drills) in comparison to match play. Small-sided games were implemented in the training programme since it suggested that a valid physical response can be gained (Buchheit et al., 2014; Carling, 2013) whilst also enhancing tactical awareness (Dellal et al., 2012). With ‘physical’ response being used to describe physiological, notational and biomechanical parameters of performance in literature, this term warrants greater consideration. Research conducted by Owen *et al.* (2012) measured physical response by analysing soccer training (5Hz GPS units) of 10 elite male soccer players (age 27.6 ± 4.11 years; height 184.1 ± 6.02 cm; mass

79.8 ± 7.91 kg) from a Scottish Premier League team that included small-sided games (small-sided games: 4 vs. 4) in comparison medium-sided games (medium-sided games: 5 vs. 5, 6 vs. 6, 7 vs. 7, 8 vs. 8) and large-sided games (large-sided games: 9 vs. 9, 10 vs. 10, 11 vs. 11) revealed that small-sided games induce significantly greater average speed in comparison to medium-sided games and large-sided games (small-sided games: 150.5 m·min⁻¹, medium-sided games: 108.3 m·min⁻¹, large-sided games: 120.4 m·min⁻¹, $p < 0.01$). High-intensity efforts (> 21.6 km·h⁻¹) during small-sided games were significantly less to large-sided games (0.88m vs. 4.40 m, $p < 0.01$) in addition to high-speed running (21.6 - 25.2 km·h⁻¹; 7 vs. 39 m, $p < 0.01$) and sprinting (25.3 km·h⁻¹: 0 vs. 11 m, $p < 0.01$). As research suggests small-sided games may not replicate high-intensity and repeated-sprint demands due to pitch dimensions not allowing players to accelerate as observed in 11 vs. 11 games (Casamichana, Castellano and Castagna, 2012; Gabbett and Mulvey, 2008; Owen et al., 2012). The greatest distance recorded occurred during the medium-sided games (7 vs 7) in the study by Owen *et al.* (2012) making the intended adaptations from various formats of small-sided games determined by various factors including duration (Dellal et al., 2008; Fanchini et al., 2011; Hill-Haas et al., 2010), number of drill repetitions (Fanchini et al., 2011), pitch area (Silva et al., 2014), number of players (Aguiar et al., 2013; Castellano, Casamichana and Dellal, 2013), and rules (Casamichana *et al.*, 2014; Castellano, Casamichana and Dellal, 2013; Mallo and Navarro, 2008).

In the first study of this thesis that examined training drills in relation to match play data, average speed (recorded with 10Hz GPS units) during match play (104.2 ± 5.1 m·min⁻¹) was significantly greater to small-sided games (86.4 ± 9.1 m·min⁻¹ $p < 0.001$, ES=1.55, 95% CI 13.82-21.78) and remaining training drill categories. With reference to high-speed distance (5.5-11 m·s⁻¹) data during match play (5.10 ± 1.32 m·min⁻¹) was significantly greater than small-sided games (0.63 ± 0.52 m·min⁻¹; $p < 0.001$, ES=1.80, 95% CI 3.87-5.07). These findings were not in agreement with previous research (Owen et al., 2012).

Study one showed that small-sided games did not replicate the physical and mechanical values as total distance and PlayerLoad was lower in relation to match play contrary to previous research examining distance covered as a physical response to small-sided, medium-sided and large-sided games (Owen et al., 2012). With the exception of high-speed entries ($5.5 - 7 \text{ m}\cdot\text{s}^{-1}$) training sessions did not meet the requirements of match play. Movement pattern drills, possession drills and game-related drills recorded less distance covered than observed during competitive matches. This led to questioning the effectiveness of such drills to prepare players for competition. Movement patterns managed to successfully re-create the high-speed running demands of competitive soccer games. Possession drills, that are important in implementing tactical philosophy of the club across teams, proved to create a large standard deviation for participating soccer players. That meant some players were physically challenged while others were not as the tempo was too slow. The study recognised the large variety of drill characteristics concerning time duration and pitch dimensions could be a factor in this disparity among training and match data. Standardisation of data values per minute however was a method to reach valid conclusions.

7.2 Distance covered as a predictor of PlayerLoad

Aguiar *et al.* (2013) advocated games with fewer players to increase physiological stress and larger games to address match-specific demands (Aguiar et al., 2013). Physical response was measured through heart rate, total distance, speed and PlayerLoad and it was concluded that fewer players (3 vs. 3) elicited the greatest distance covered in comparison to larger games (4v4) while PlayerLoad was greater with more players (4 vs.4). In contrast, larger game formats have been associated with greater total distance covered (Coutts et al., 2011; Hill-Haas et al., 2009). Castellano, Casamichana and Dellal (2013) reported that PlayerLoad was highest for 5 vs 5 games, whereas distance covered was greatest in 7 vs 7 games. The increase in distance

covered is most likely a reflection on the increased pitch size for the 7 vs 7 game, but the disparity with greater Load incurred during the smaller game was not clarified. The lack of consensus is most likely reflective of the variability in the design of (and subsequent response to) small-sided games, but does highlight a lack of linear correlation between distance covered and accumulated PlayerLoad. Casamichana *et al.* (2014) quantified PlayerLoad in a comparison of ‘free play’ and conditioned ‘two touch’ small sided games of 6 vs 6, but failed to correlate this parameter with other measures of physical response. Casamichana and Castellano (2015) later did quantify the correlation between PlayerLoad and total distance during small-sided games ($r=0.75$, $p<0.001$). In the present thesis, the correlation between PlayerLoad and distance was observed to be drill-dependent. The strongest correlation with PlayerLoad and total distance ($r=0.92$, $p<0.001$) was observed for “possession” drills, but only moderate correlation was observed during match play ($r=0.37$, $p=0.19$). Study one compared training data to match play while previous research examined PlayerLoad and total distance using training data only (Aguiar et al., 2013; Casamichana and Castellano, 2015; Casamichana et al., 2014; Castellano, Casamichana and Dellal, 2013). Synthesis of this literature suggests a higher correlation between PlayerLoad and distance can be attained during training drills, rather than during regulation 11 vs 11 match play. The influence of game design on this correlation is understandable when the calculation of PlayerLoad is considered. Load is accumulated only when an acceleration takes place, and thus running at constant velocity in a straight line would accrue no increase in PlayerLoad. Where the activity profile is characterised by a higher frequency of speed and directional change, a greater PlayerLoad would be accumulated. Thus distance per se is not the determining factor, rather how the player moves will determine the accumulation in PlayerLoad. Where distance is accumulated with a high frequency of speed and/or directional change, the correlation between distance and PlayerLoad will be stronger. In study 1, up to 90% of the variance in PlayerLoad can be accounted for

by changes in distance during possession drills for example, suggesting it is these drills which created an activity profile characterised by the highest frequency of speed and/or directional change. The higher sampling frequency of the acceleration data at 100Hz in comparison to the 10Hz positional data used to derive distance covered is also a likely source of disparity.

Study one recorded a strong correlation between PlayerLoad and total distance during some training sessions, but only a moderate correlation during match play. In study two the correlation between PlayerLoad and total distance during match play for the three age groups analysed (U16, U18, U21) ranged from $r=0.26-0.56$, with evidence of higher coefficients in the U16 group. This higher correlation coefficient is indicative of a higher frequency of directional or speed change in the younger group. This difference in activity profile, with the younger players exhibiting a greater frequency of intermittent and multi-directional activity might be attributed to game management and experience. The U16s covered the greatest distance while the U18s recorded the greatest PlayerLoad, supporting this apparent contradiction observed in small-sided games (Aguiar et al., 2013; Castellano, Casamichana and Dellal, 2013).

In study three the correlation between PlayerLoad and total distance was found to be position specific with forwards recording the strongest correlations ($r=0.74$). In contrast midfielders exhibited a correlation of only $r=0.16$, reflecting the difference in activity profile, and most likely attributable to a difference in tactical remit. Midfielders covered the greatest distance, but the highly intermittent and multi-directional nature of forward play, along with the emphasis on high-speed entries, promotes the accumulation of PlayerLoad. A box-to-box midfielder who covers most distance at a constant velocity would accrue a high total distance covered, but not accumulate PlayerLoad without a change in acceleration.

In study four where a new method of calculating PlayerLoad (*iLoad*) was proposed the correlations for PlayerLoad and total distance during match play were consistent with the

findings with the previous experimental chapters of the thesis. The fundamental difference in the calculation of PlayerLoad based on the rate of change in acceleration with or without a consideration of magnitude was highlighted in the lack of correlation between the parameters. The highest r value observed at 0.35 would still only explain 12% of variance. In this respect the two parameters must be considered discrete. PlayerLoad was observed to have a stronger correlation with distance covered (1st half $r=0.36$, $p<0.001$, 2nd half $r=0.33$, $p<0.001$) than i Load (1st half $r=0.19$, $p=0.05$, 2nd half $r=0.19$, $p=0.04$). These findings did not support previous research (Casamichana and Castellano, 2015) that examined small-sided games and the correlation between PlayerLoad and total distance ($r=0.75$, $p<0.001$) with PlayerLoad calculated as a summation of three acceleration planes. This lends to the distinction of total distance and PlayerLoad as fundamentally different measurements. Correlations found in previous research were being based on the calculation of PlayerLoad as a summation of three force planes (Aguiar et al., 2013; Casamichana and Castellano, 2015; Casamichana et al., 2014; Castellano, Casamichana and Dellal, 2013).

This highlights another limitation in the use of PlayerLoad as calculated from tri-axial accelerometry, in that it is not clear in which movement plane the player has changed acceleration. Changing direction would result in a change in PlayerLoad even at constant velocity, since the directional change (for example from forward to sideways) would elicit a change in PlayerLoad in both planes, with an increase in medio-lateral Load and a concurrent decrease in antero-posterior Load. Thus a high frequency of speed change or directional change, rather than necessarily a greater total distance covered, will elicit higher PlayerLoad values. This mechanistic evaluation of the calculation in PlayerLoad explains the difference in strength of correlation with distance based on the movement characteristics of each drill. This also highlights the limited use of tri-axial accelerometry when only considering total accumulated PlayerLoad with no consideration of the relative movement planes.

7.3 Uni-axial load

In the first experimental study the parameters included in the analysis were selected and utilised on a daily basis by the football club for performance monitoring purposes of both training sessions and matches. Tri-axial accelerometry embedded in the portable GPS units only provided a total accumulated PlayerLoad value. As discussed above, this variable calculates instantaneous change in acceleration across three movement planes through the formula described by Boyd, Ball and Aughey (2011). A limitation of this calculation lies in the summation of accelerations as total PlayerLoad would not actually be the sum of the three individual planes because of the interpretation of the square root function (as described in Chapter one). Limited research to date has been devoted to the new phenomena of uni-axial accelerometry. In a recent study analysing fast bowling in cricket, the loading pattern of medio-lateral load was linked to injury prevalence (Greig and Nagy, 2016). Uni-axial loading follows the principle of force plate analysis in a laboratory setting and is more representative of biomechanical analysis. The three vector planes are discrete thus total ground reaction force would not be considered. The relationship between force and acceleration defined through Newton's Law is fundamental to biomechanics and uni-axial acceleration should not be neglected in movement analysis. Further, the inherent error in the calculation of PlayerLoad limits the interpretation of movement quality, since it is not possible to determine in which plane load was accrued. In experimental studies two and three collection of accelerometry data acquired during match play was retrospectively analysed to consider each uni-axial acceleration; medio-lateral, antero-posterior and vertical.

Experimental study two analysed three age groups (U16, U18, U21) with reference to PlayerLoad through analysis of uni-axial accelerometry. Total PlayerLoad across the three planes recorded for the U18 team ($az\ 558.5 \pm 85.2\ AU$; $ay\ 384.1 \pm 86.7\ AU$; $fx\ ax\ 310 \pm 45.82\ AU$) was significantly different than U16 ($az\ 480 \pm 25\ AU$; $ay\ 300.2 \pm 42\ AU$; $ax\ 141.5 \pm 17.4$

AU) and U21 teams ($az\ 465.98 \pm 29.75\ AU$; $ay\ 314.3 \pm 48.3\ AU$; $ax\ 134.2 \pm 18\ AU$). The findings of the U18 team revealed a unique movement profile across each directional plane where double the amount of medio-lateral load was recorded. Subsequently, the U18 team also presented a unique relative planar contribution to loading in $ax:ay:az$ as 25:30:45, compared to $\sim 15:33:52$ for the U16 and U21 teams. This contribution ratio of PlayerLoad revealed a unique movement strategy of the U18 team as the decrease in vertical and antero-posterior planes (compared to U16 and U21 teams) was compensated by an increased medio-lateral contribution to PlayerLoad.

As discussed previously, the accumulation of PlayerLoad is based on an instantaneous change in acceleration. For total accumulated PlayerLoad this can be attributed to a change in direction or speed. For uni-axial loading this accumulation of planar Load can only be achieved with a change in acceleration, and thus the implication is that the U18 players are completing more accelerations in the sideways direction. This is indicative of greater lateral movement.

Experimental study three examined the U18 age group on a positional basis in order to further analyse the unique movement pattern recorded in uni-axial accelerometry of PlayerLoad. Midfielders exhibited significantly greater vertical Load than defenders, and significantly greater antero-posterior load than forwards. Midfielders and forwards produced greater medio-lateral Load than defenders. These observations are of interest in defining the activity profile and specific movement demands of each position, with implications for training design. Further analysis of positional classifications revealed that defenders (wide and central) and forwards (wide and centre) exhibited significant differences in relation to uni-axial accelerometry of PlayerLoad. Wide defenders exhibited more antero-posterior Load than central defenders, indicative of more progressive movement up the pitch, and a tactical remit to contribute to offensive strategies. Midfielders exhibited the greatest antero-posterior Load,

most likely reflective of a tactical remit to work from “box-to-box”. Conversely, central forwards and defenders exhibited the lowest antero-posterior Load.

Wide defenders, with a high antero-posterior Load, exhibited a lower medio-lateral Load than midfielders, reflective of their positioning toward the periphery of the pitch and thus with less options to accelerate laterally. Interesting, wide attackers produced greater medio-lateral Load than defenders, with these two positions likely to be matched on the pitch. Tactically, there might be greater freedom for the attacking players to move laterally without compromising the shape of a team. This might be reflective of greater flexibility in the attacking unit, with a more constrained ‘shape’ adopted by the defensive unit. Central defenders and central forward also exhibited less medio-lateral Load than midfielders. This positional sensitivity in uni-axial loading patterns suggests potential in supplementing notational analysis. The movement demands of each position appear unique from a loading perspective, as a response to their individual technical and tactical remit. This highlights the movement quality potential in tri-axial accelerometry, but also the opportunity to further develop position-specific training regimes.

The findings of experimental study three can be utilised as performance markers in the same manner previous soccer research of position and the relationship to total distance has led to player profiling (Andrzejewski et al., 2012; Di Salvo et al., 2013 Bradley et al., 2011; Terje et al., 2016). A representative biomechanical profile of playing position was created with implications for training preparation. The highest PlayerLoad observed in midfielders may be indicator of game requirements, linking defenders and attackers. Wide attackers exhibited significantly greater mediolateral contribution to total Load. This is indicative of greater lateral movement, potentially both with and without the ball. Conversely, central attackers exhibited greater vertical Load, potentially as a result of more heading duels, and a compensatory decrease in antero-posterior contributions to loading. This would suggest that the forwards in

this formation (4-4-2) do not play in straight lines, but rather complete a high level of fast, multi-directional movements. Defenders recorded significantly less medio-lateral Load than midfielders and forwards, and the interaction of the various positions will have implications for the biomechanical demands. Whilst these positional remits are designed around technical and tactical remits, the physical implications might inform the development of position-specific physical training programmes. This sensitivity in analysis highlights a potential merit in tri-axial accelerometry.

Secondary analysis across five playing positions revealed that wide attackers (or wingers) shared a similar movement pattern to their defensive counterparts. Therefore, the secondary analysis was successful in providing a precise movement profile that revealed that within the sub-categories of defenders (wide and central) and forwards (wide attackers and centre) there are significant differences to midfielders. This might suggest player groupings based on wide vs central rather than defender vs midfielder vs central. In the context of the football club, technical staff would hold “unit meetings” with a traditional grouping of defenders, midfielders, forwards. The same units are often applied in physical work, and these biomechanical observations warrant consideration in the grouping of players.

7.4 Sign and Magnitude of acceleration

Experimental studies two and three provided new insight into the loading patterns exhibited during soccer with a consideration of uni- (rather than tri-) axial loading. Through uni-axial accelerometry a more rigorous movement profile was created that can strengthen the developing body of applied biomechanics research in soccer (Barron et al., 2014; Page et al., 2015). These studies have targeted the mathematical flaw in the calculation of PlayerLoad, where the summation principle is erroneous and the 3D value negates further understanding of movement characteristics. In the final experimental study this critical mechanical analysis of

the PlayerLoad calculation was examined further. Whilst uni-axial loading provides a more biomechanically rigorous understanding of movement than tri-axial patterns, there are still inherent assumptions which limit interpretation. To further the force plate analogy used previously in the context of a 'total' ground reaction force, the vector magnitudes in force are considered with a sign convention applied as standard. For example, negative medio-lateral force would be inversion, and positive force eversion. The application of this sign convention is fundamental in the analysis of sporting movements, with applications in performance enhancement and injury prevention. To not differentiate between inversion and eversion would be fundamentally limiting.

In the calculation of PlayerLoad the instantaneous change in acceleration is squared. This negates the presence of negative values. Thus all data is considered to be right, forward, and upward, i.e. the positive elements of acceleration in the medio-lateral, antero-posterior, and vertical planes. This negates the opportunity to consider dominance in medial and lateral loading, or acceleration, and the analysis of backward running which might be position specific. In a recent paper, Brown and Greig (2016) used this sign convention to highlight a 3:1 imbalance in medio-lateral loading in a case study of a recurrent lateral ankle sprain in a professional soccer player. As a performance metric, some players might have a tactical remit, or a technical preference for medial vs lateral (left vs right) movement, but this would not be apparent in the current calculation of PlayerLoad. As previously stated, squaring and summation of directional vectors negates both the magnitude of acceleration and relative contribution of across each movement plane. Disregarding the difference between medial and lateral movement reduces the potential of in depth analyses in sports biomechanics. Acceleration, as a vector quantity has both magnitude and direction therefore tri-axial accelerometry should not negate either factor.

The final experimental study applied an additional level of mechanical investigation by considering the magnitude of acceleration. The proposed formula for the calculation of *iLoad* provides both magnitude and orientation across movement planes to provide a representative biomechanical profile of elite level soccer performance. This mathematical interpretation was applied to an analysis of fatigue, with both injury (Ekstrand et al., 2011a) and performance (Mohr, Krstrup and Bangsbo, 2003) susceptible to the influence of fatigue during the latter stages of matches. Carling (2013) states that research in the area of soccer performance analysis has reported the existence of fatigue during match play however the failure to discuss the extrinsic and intrinsic factors that can affect data poses a concern. Further, declines of a few hundred metres in total distance covered may not be always significant or meaningful (Carling, 2013).

In experimental study four, both *iLoad* and PlayerLoad formulas were used during match play across each movement plane. Mediolateral *iLoad* was distributed across medial (-ve ax, left) and lateral (+ve ax, right) movement. Mean -ve ax (orientation to the left) was -119.6 ± 58.8 arbitrary units and +ve ax (orientation to the right) was 93.7 ± 45.3 arbitrary units. It was found that -ve ax was slightly larger than +ve ax, that indicates dominance, however there was no statistical main effect for time. This medio-lateral ratio is not comparable to the 3:1 ratio observed by Brown and Greig (2016) in an injury context.

Anteroposterior *iLoad* produced a ratio of ~6:1 for forwards:backwards acceleration, but there was no significant main effect for match time. This dominance in the forward direction is not surprising, but potentially does have implications from a strength and conditioning perspective. Similarly, the majority of vertical movement is conducted in the +ve az. Statistical main effect for time was found in -ve az at 75-90 minutes in comparison to 15-30 minutes ($p=0.037$), 30-45 minutes ($p=0.018$) and 60-75 minutes ($p=0.015$). Conversely, vertical PlayerLoad recorded no significant main effect for time during match play. The vertical plane is the dominant plane

of movement as recorded in experimental studies two, three and four. With the significant decrease in both landing and take-off phases recorded in the final 15 minutes of match play it is reasonable to consider a fatigue effect. Epidemiological observations consistently report a higher incidence of injury during the latter stages of match play (Ekstrand et al., 2011a).

The values of *iLoad* were greater since they provided a representation of magnitude of acceleration. Load describes instantaneous change in magnitude and more frequent changes in acceleration amplify this. PlayerLoad does not include magnitude of acceleration and the resulting outcome aside from a mathematical flaw is creating an erroneous value of the load that soccer players produce during match play. Further orientation of the magnitude of acceleration provides precise information on the movement pattern of soccer players during match play. Such qualitative analysis provided insight into the dominant vertical plane of movement. *iLoad* calculated the significant main effect for time in $-az$ (landing) during the last 15 minutes of match play in comparison to all previous segments, indicative of fatigue. Vertical PlayerLoad recorded no significant main effect for time as a result of the formula utilised that does not factor in magnitude and orientation of acceleration. The novel calculation of mechanical load provides data analysis of two previously disregarded parameters, magnitude and acceleration. Biomechanical theory and practice states that in the case of movement vectors planes should not be summated and then squared as in the case of PlayerLoad. Therefore, *iLoad* applies the methods used in a laboratory setting to analyse movement and technique. The innovation in this instance lies in the ability of portable GPS technology to now measure accelerations across movement planes through the application of biomechanical theory.

The lack of correlation, and intuitive relationship between distance covered and PlayerLoad was discussed previously. Study four also highlighted that *iLoad* is a discrete parameter as the two variants of load were not correlated. The calculation of *iLoad* with consideration of magnitude underlines the fundamental difference to PlayerLoad. The lack of correlation

between *i*Load and total distance further supports the discrete nature of such variables with *i*Load providing a representative profile of the biomechanical demands of soccer match play. The innovation in the soccer mechanics of experimental study four lies in the orientation of movement.

7.5 Future applications of research

The GPS technology applied in soccer training has reported PlayerLoad as a single value without consideration of movement orientation (Aguilar et al., 2013; Casamichana and Castellano, 2015; Casamichana et al., 2014; Castellano, Casamichana and Dellal, 2013). This warrants future research in soccer to be conducted with a consideration of uni-axial load to discover the dominant plane of movement as analysed in this thesis. This method of analysis has been recently applied to cricket where a loading pattern linked to injury was discovered (Greig and Nagy, 2016). Uni-axial loading stems from biomechanical principles of force vector planes being discrete, therefore future research should provide a more representative analysis of data on that basis.

Research has concluded that the majority of lower extremity injuries located at the ankle, adductor, and quadriceps occur on the dominant leg (Ekstrand, Hägglund and Waldén, 2011a; Hägglund, Waldén and Ekstrand, 2013; Hawkins et al., 2001; Woods et al., 2003). Through the application of *i*Load dominant side of movement was established creating opportunity for future investigation of dominant and non-dominant loading profiles of soccer players. Embedded in the *i*Load formula is the sign convention of movement. Differentiation between medial and lateral movement for example has applications in injury monitoring (Greig and Brown, 2016). This methodology can be applied to future research of movement screens by highlighting potential deficiencies that could increase susceptibility to injury. Research in this area could provide the insight on corrective movement mechanics for example and improving

performance without potential clinical intervention. The rehabilitation phase of soccer players until their return-to-play is an area of potential research also. Monitoring the orientation and magnitude of load soccer players produce during such a crucial part of performance could provide fitness coaches and physiotherapists with a representative biomechanical profile of players.

Placement of the GPS unit is usually at the cervico-thoracic junction in the specialised garments designed by the providers of this technology. Research conducted in soccer has included different locations of the GPS unit on the scapulae and centre of mass (Barrett et al., 2016). However, the centre of mass moves and is a theoretical construct, of little relevance to soccer research. Greig and Nagy (2016) used the lumbar vertebrae to compare to the thoracic vertebrae during fast bowling in cricket. This was mechanically valid given the epidemiology of back injuries in cricket. Loading patterns were consistent with injury incidence and aetiology, with the uni-axial medio-lateral plane highlighting significantly greater rotation at the lumbar spine. Future research opportunities exist in placing the GPS units on the lower extremities (hamstrings, quadriceps) and with the *iLoad* calculation measure the magnitude of acceleration. The measure of tri-axial acceleration at 100Hz provides an opportunity to further analyse specific movements in isolation. The application in this thesis to a 90-minute match negates the opportunity for refined movement analysis. However, the opportunity to apply these tri-axial analyses parameters to more discrete and standardised movements offers potential. For example, a standardised cutting or agility task could be analysed in great detail, highlighting the tri-axial accelerometry patterns in the same way a force platform would be used. The added external validity afforded by GPS micro-technologies over the laboratory environment would enhance the application of sports biomechanics in soccer. Assuming constant mass, force and acceleration are linearly related by Newtonian mechanics. At 100Hz the sampling frequency of accelerometry is lower than a typical force platform setting, but a direct comparison would

be of interest. The use of multiple units would also then enable an investigation of force attenuation through the body. Ground reaction force will be highest, but an efficient mechanical system will then dissipate load such that the acceleration at the cervico-thoracic junction is much lower. This would be of particular interest for the quantification of lower limb kinetics in tasks such as plyometrics. In the (p)rehabilitation context this additional rigour in movement mechanics would also offer great potential, for example in identifying movement asymmetry during simple, early-stage rehabilitation.

The manipulation and monitoring of loading from an injury perspective could be further applied to the influence of playing surface. Soccer pitches with artificial turf and natural grass have been areas of scientific research with relation to injury incidence during matches and training. Studies have reported an increased rate of ankle injuries on artificial turf and greater muscle soreness (Ekstrand, Timpka and Häggglund 2006; Poulos et al., 2014). The impact of playing surface is an area where future scientific investigations can be formulated.

The thesis has provided opportunities for future research through the analysis provided in the experimental studies. Performance audits, similar to the analysis of training and match play in study one, can be applied to additional teams. This process will provide the information necessary to monitor the extent of training principles and design preparing players for game demands. Age groups and playing position have been shown to produce distinct movement profiles and research can introduce the biomechanical indicators of performance as a tool for match performance evaluation. The development of *iLoad* can now address the mathematically flawed *PlayerLoad* formula currently used in portable GPS technology. Soccer research can be at the forefront of future research in quantification of magnitude and orientation of load and this application can be transferred to an array of sports.

CHAPTER 8. Conclusion

This research project provided novel biomechanical findings that will assist practitioners in areas of training, coaching, match play with a future outlook on injury prevention and/or mechanisms. The wide spectrum of application of the experimental studies integrates sport scientists, coaches, technical directors, physiotherapists and medical doctors. The value of such research lies in the application of biomechanical theory onto the pitch for the benefit of soccer players. The first study was based on current practice at an elite academy, and highlights the limitations of the PlayerLoad metric as a parameter of training intensity. Improving the method of calculating mechanical load was the foundation of such scientific research and this has been achieved through the in depth data analysis throughout the thesis.

The lack of correlation between distance covered and PlayerLoad highlights an erroneous assumption of some intuitive relationship. Covering greater distance does not necessarily imply greater accumulation of Load, as distance is not featured in the calculation of PlayerLoad. Only a change in acceleration will create an increase in accumulated PlayerLoad. This feature of the PlayerLoad equation used prominently in professional soccer as a marker of intensity is problematic, and limits our understanding. Mechanical intensity should therefore be considered to be related more to how we move than how far.

The tri-axial accumulation of PlayerLoad is also misrepresented in the typically used formula. The summation and sign principles are negated, such that total accumulated PlayerLoad does not equate to the sum of the three directional vectors, and there is no way to differentiate forwards and backwards (or left vs right) movement. This contradicts many of the first principles employed in biomechanical analysis of movement kinetics. The tri-axial function of the accelerometer is best utilised by a consideration of each uni-axial vector. This would increase our understanding of the movements performed by the Player.

A percentile contribution of each axis to total PlayerLoad is preferable to a PlayerLoad value which underestimates the sum of the three vectors. The further consideration of sign convention, negated by the squared function in the original equation, further increases our understanding of movement and offers potential for inclusion as an analysis parameter. Arguably over 90 minutes this is a vast amount of information with difficulty in isolating the specific movement being conducted by the player, but the consideration of (for example) medial and lateral accelerometer bring the GPS analysis closer to the 'gold standard' kinetic measure using force platform technology. Here the high sampling frequency of the accelerometer (vs GPS) might be best applied to shorter, discrete movements. Sign convention and magnitude are a positive advancement of the application of biomechanical theory in an applied setting through the use of portable GPS technology. Therefore, the thesis addressed the application of the biomechanical findings in performance monitoring and future opportunities to develop this concept further. The application to both performance and injury warrants further consideration.

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Appendix 1

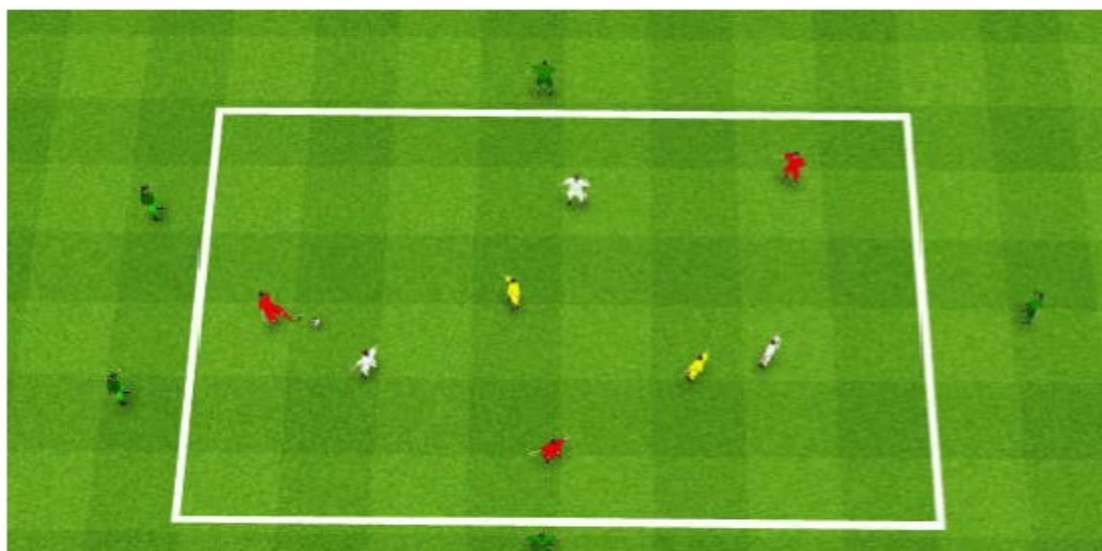
Schematic representation of training drills

Possession Drills

Possession 3v3 +2

Area: 22metres x 16metres

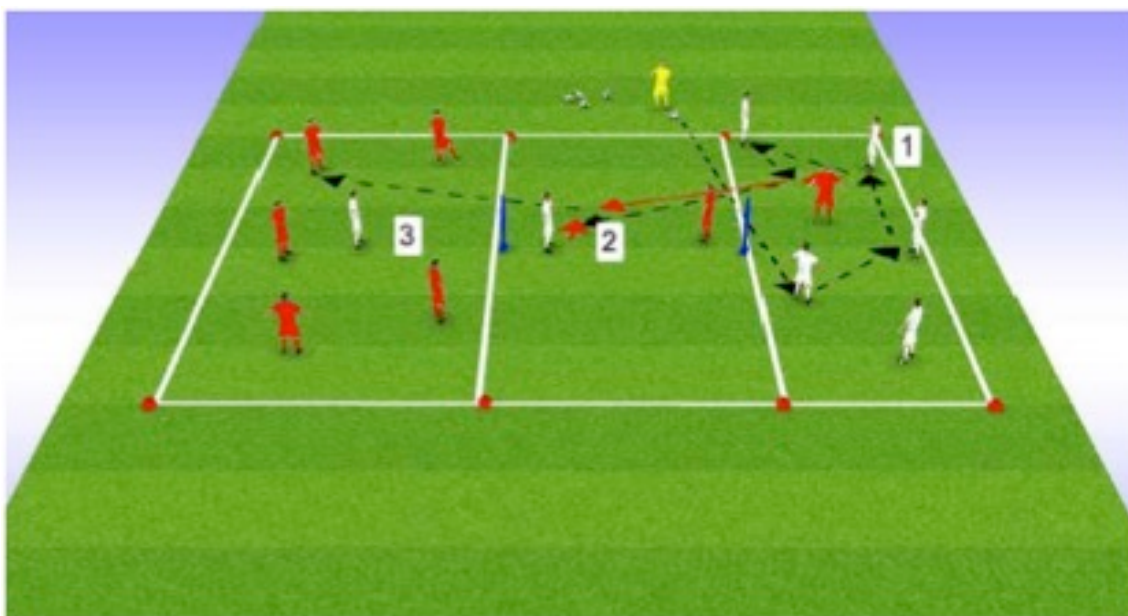
Duration: 3 x 4 minutes, 1 x 3 minutes, 1 x 2 minutes



5 v 1/ 2players in end zones

Area: 39 metres x 18 metres (top); 15 metres x 18 metres (middle)

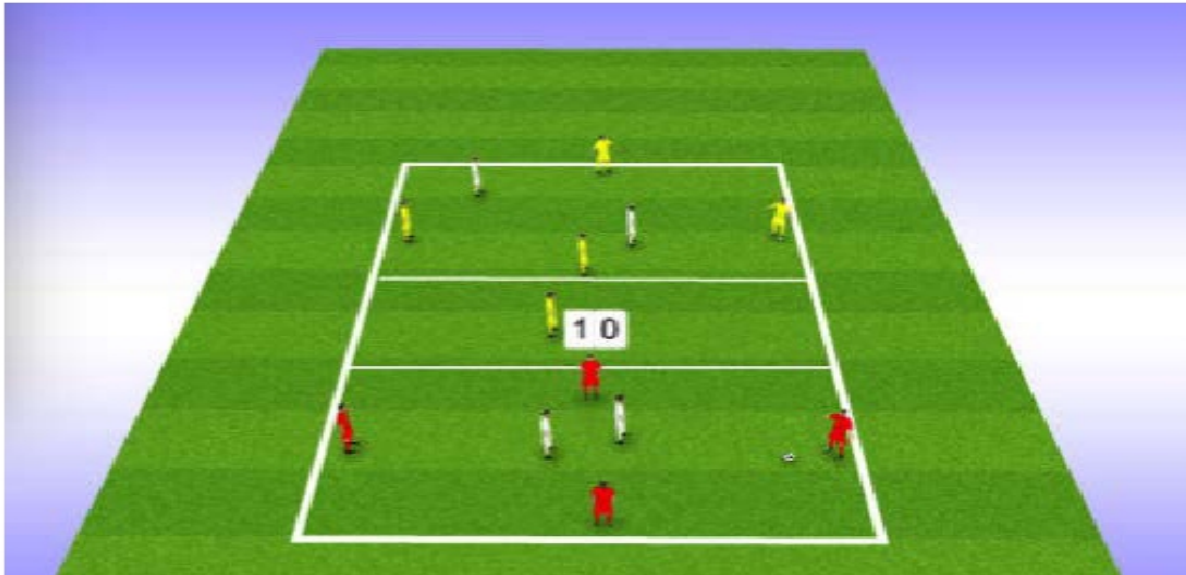
Duration: 3 x 3 1/2 minutes



Possession transfer 4v2

Area: 24 metres x 13 metres; 8 metres x 13 metres (end zones)

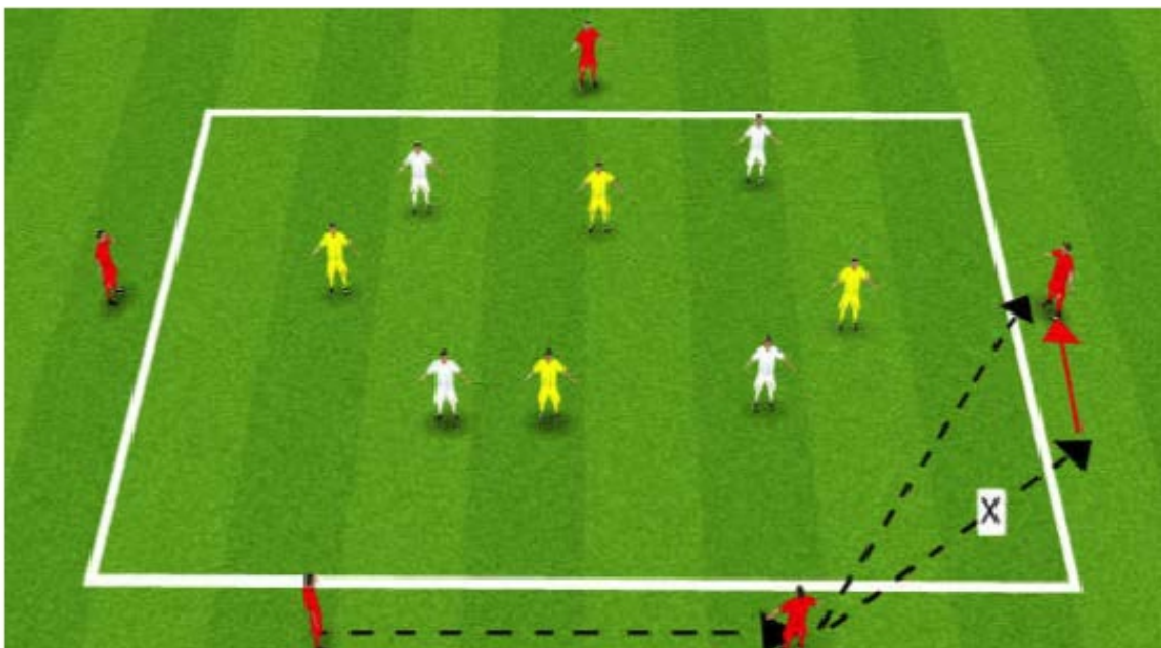
Duration: 3 x 3 minutes



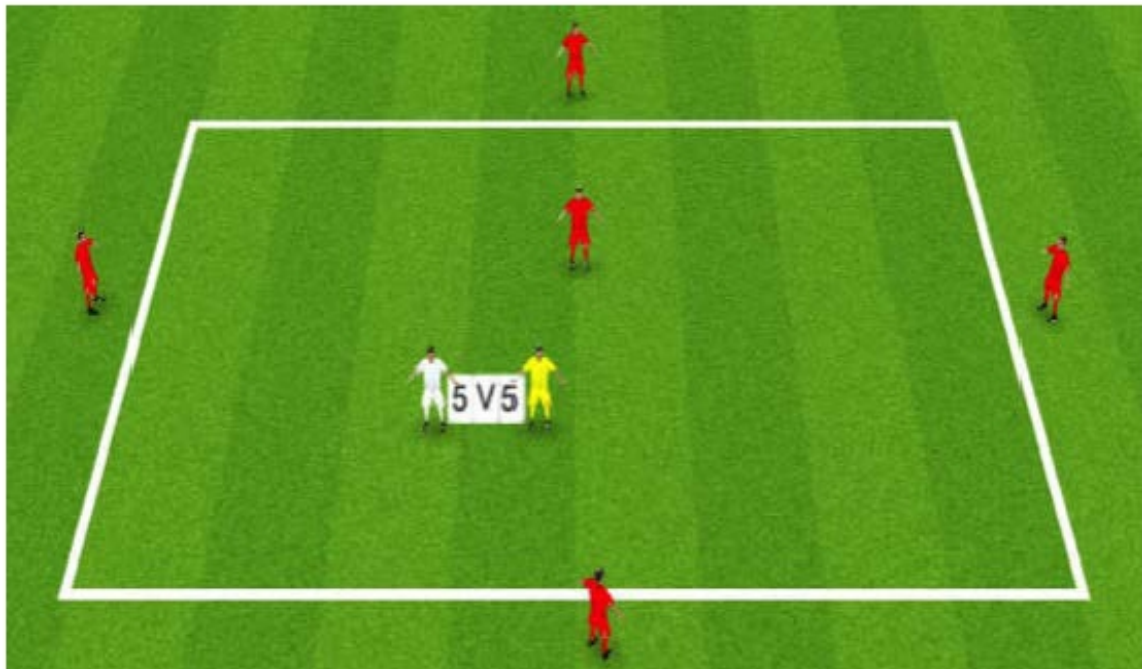
Possession 4 v 4 + 1 break line with and without the ball

Area: 20 metres x 17 metres

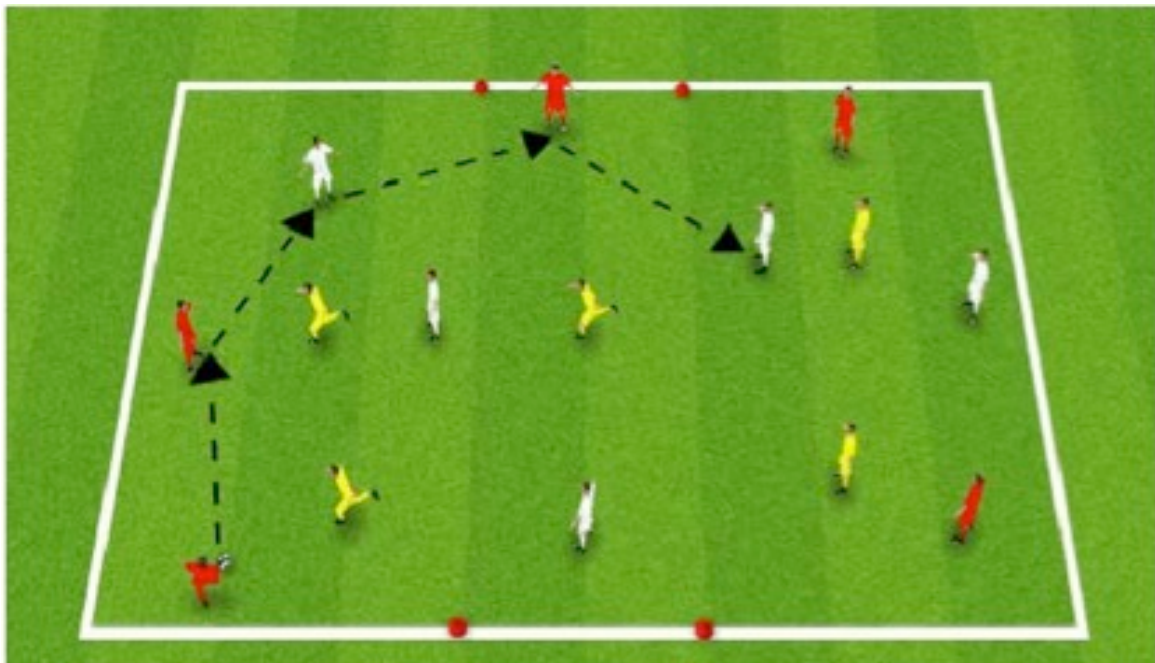
Duration: 3 x 2 minutes (per team)



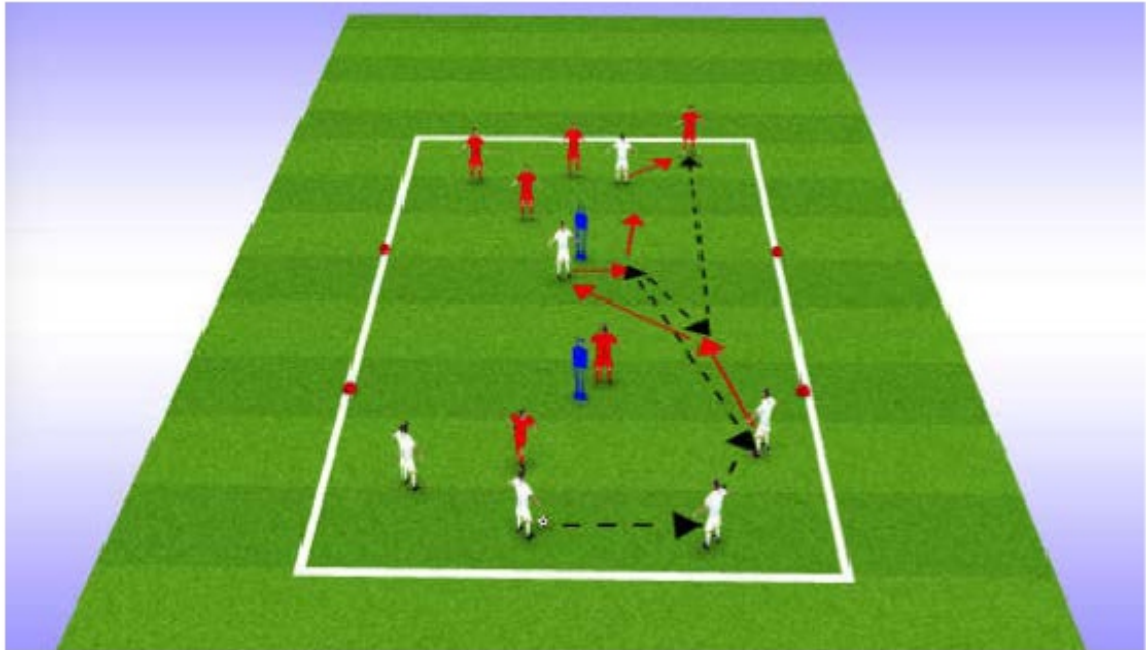
Possession 5 v 5 + 2 goalkeepers + 2 floaters, retain possession using all players
Area: 32 metres x 8 metres
Duration: 6 x 3 minutes



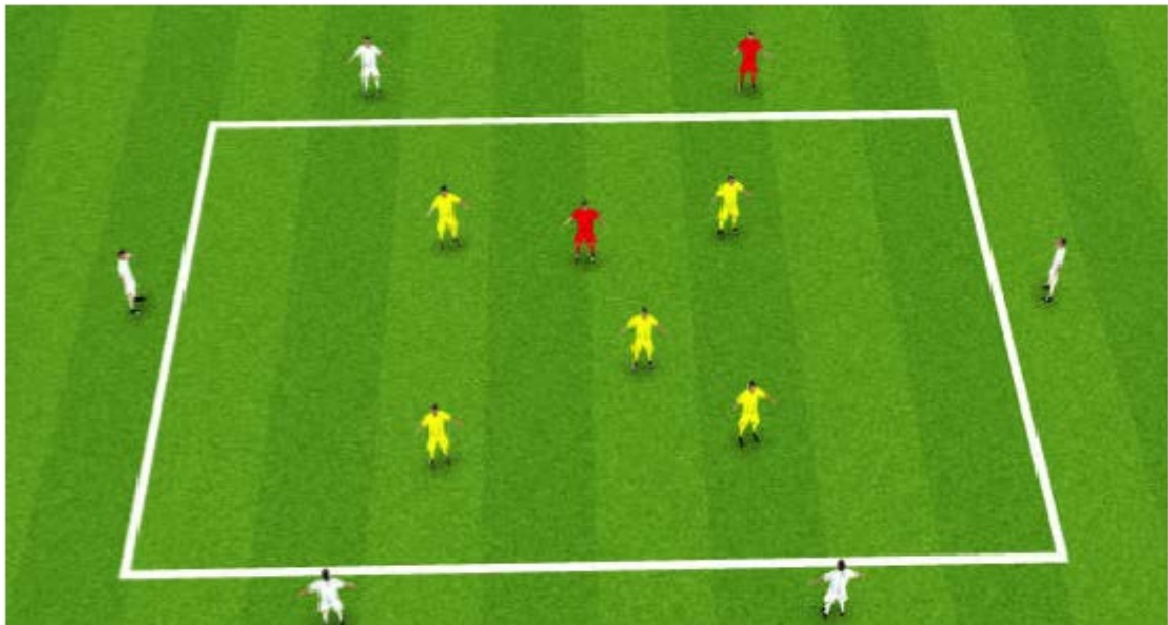
Possession 4 v 2
Area: 35 metres x 18 metres
Duration: 5 x 2½ minutes



Possession, team in end zone retain ball until pass to front man is made
Area: 36 metres x 16 metres
Duration: 3 x 4 minutes



Possession 5 v 5, opposite movement # 9, # 10 (red), defense (yellow)
Area: 23 metres x 20 metres
Duration: 6 x 3 minutes



Possession 4 v 4 + 1 + 2 end players

Area: 21 metres x 21 metres

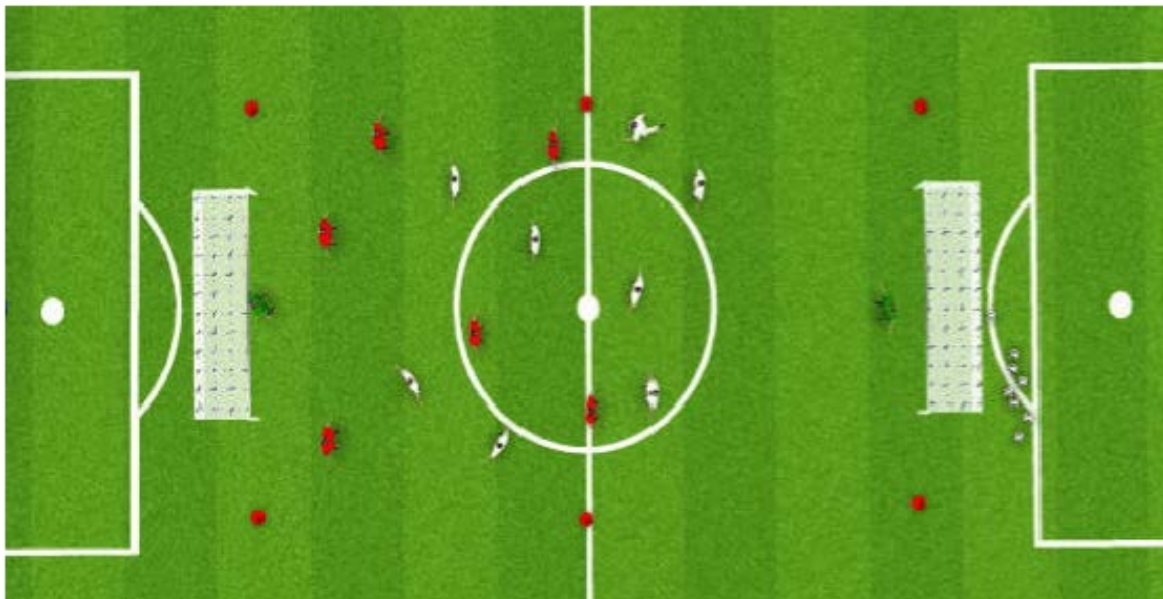
Duration: 3 x 3 minutes



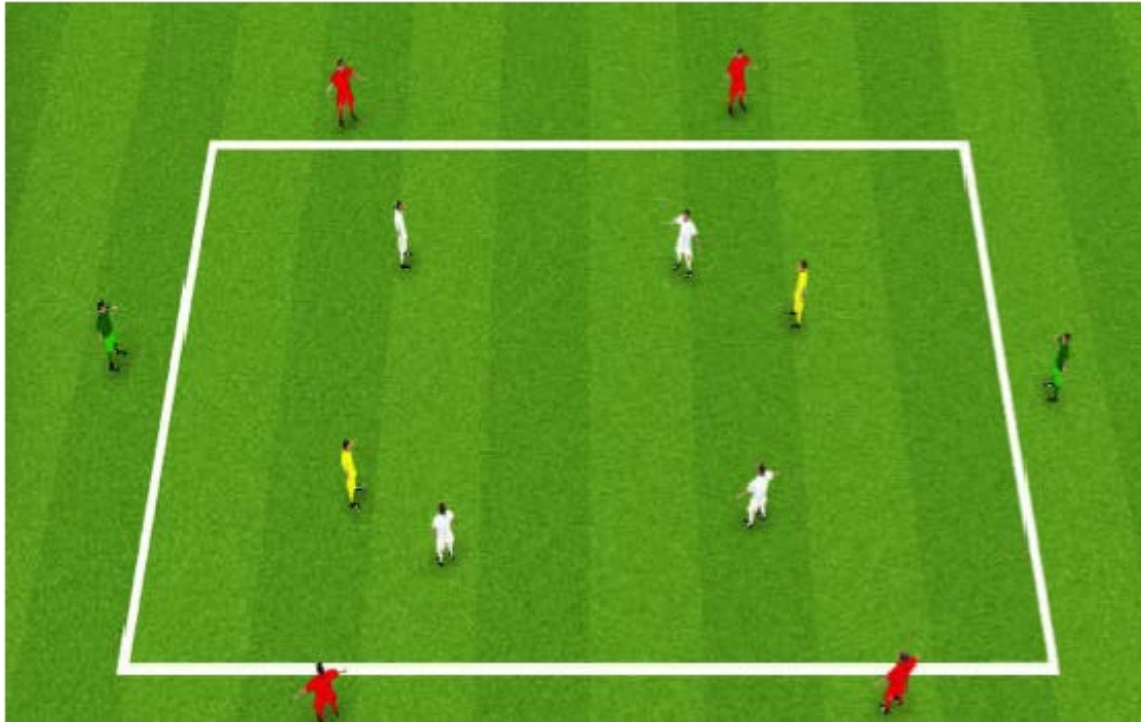
Possession 8 v 6

Area: 36 metres x 36 metres

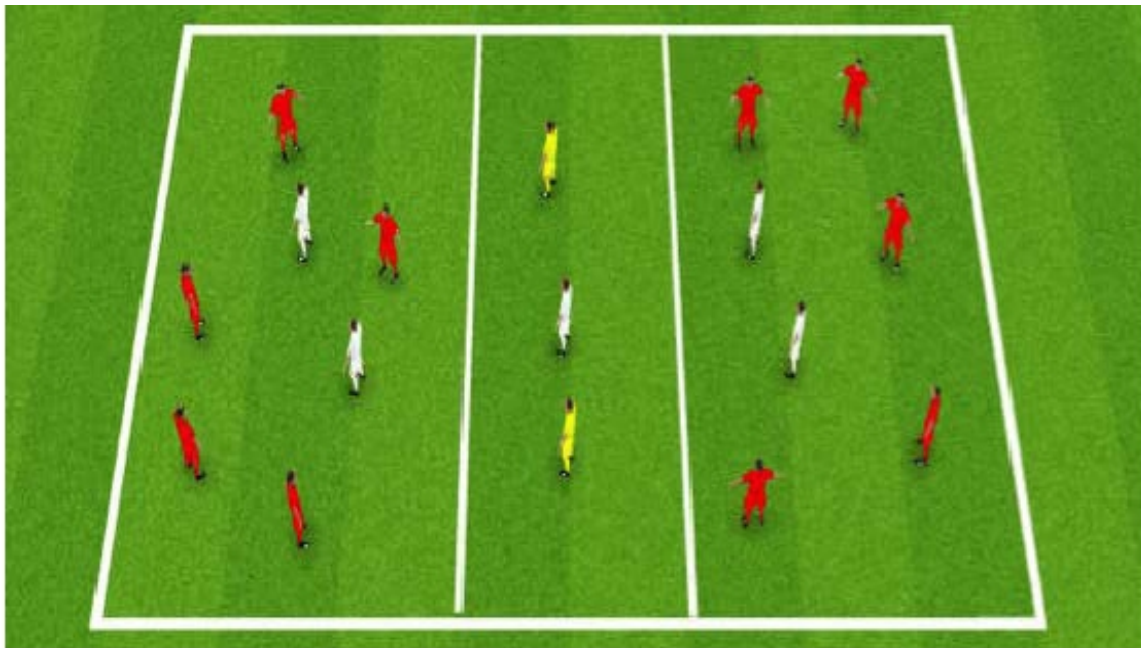
Duration: 1 x 3 1/2 minutes; 2 x 4 minutes



Transitional possession
Area: 22 metres x 18 metres
Duration: 6 x 2 minutes



Possession, play through middle 1/3
Area: 35 metres x 19 metres; 12 metres x 19 metres (end zone)
Duration: 6 x 3 minutes

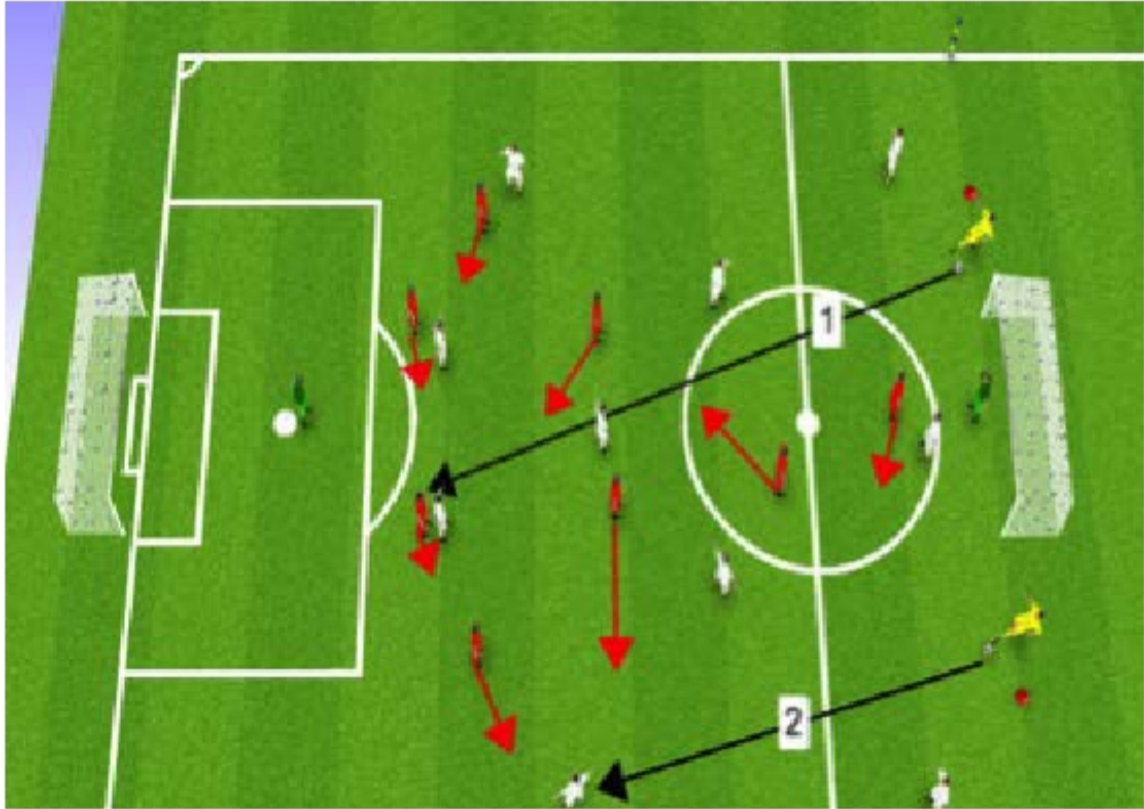


Movement Pattern Drills

Defensive Shape

Area: Half pitch

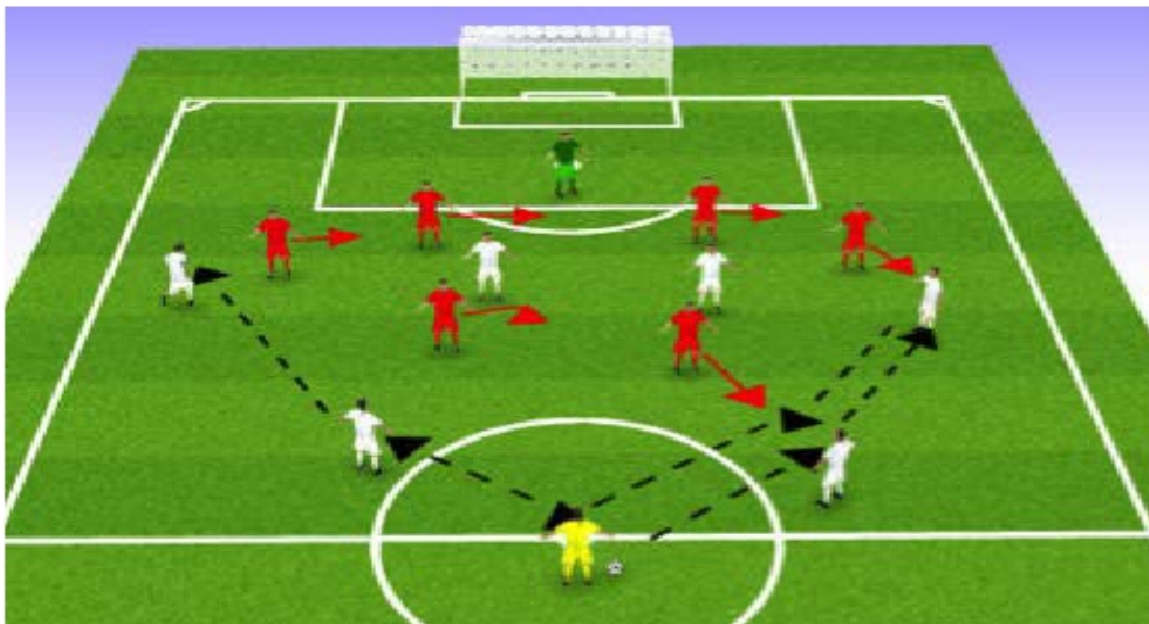
Duration: 6 minutes



Defensive Shape 6 v 6

Area: Half pitch

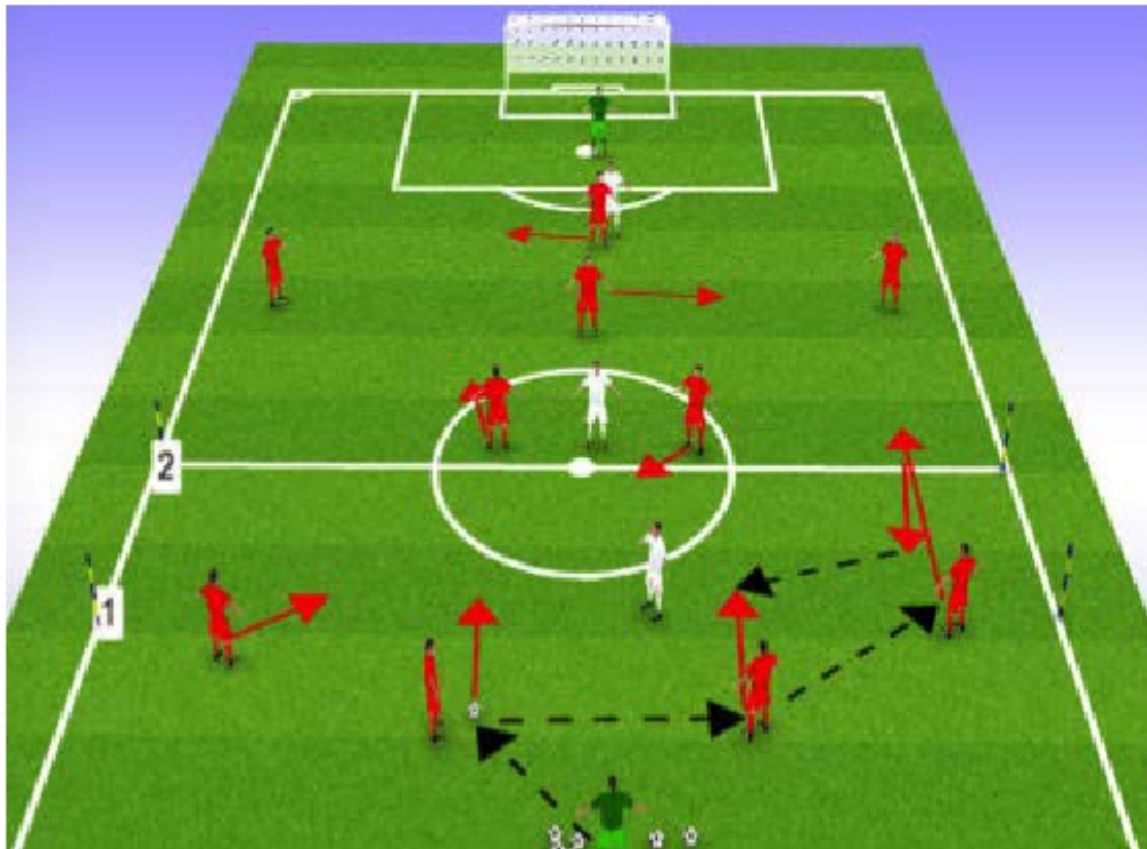
Duration: 7 minutes



Movement Pattern, passing through each position

Area: Half pitch

Duration: 3 x 3 minutes, 1 x 4 minutes



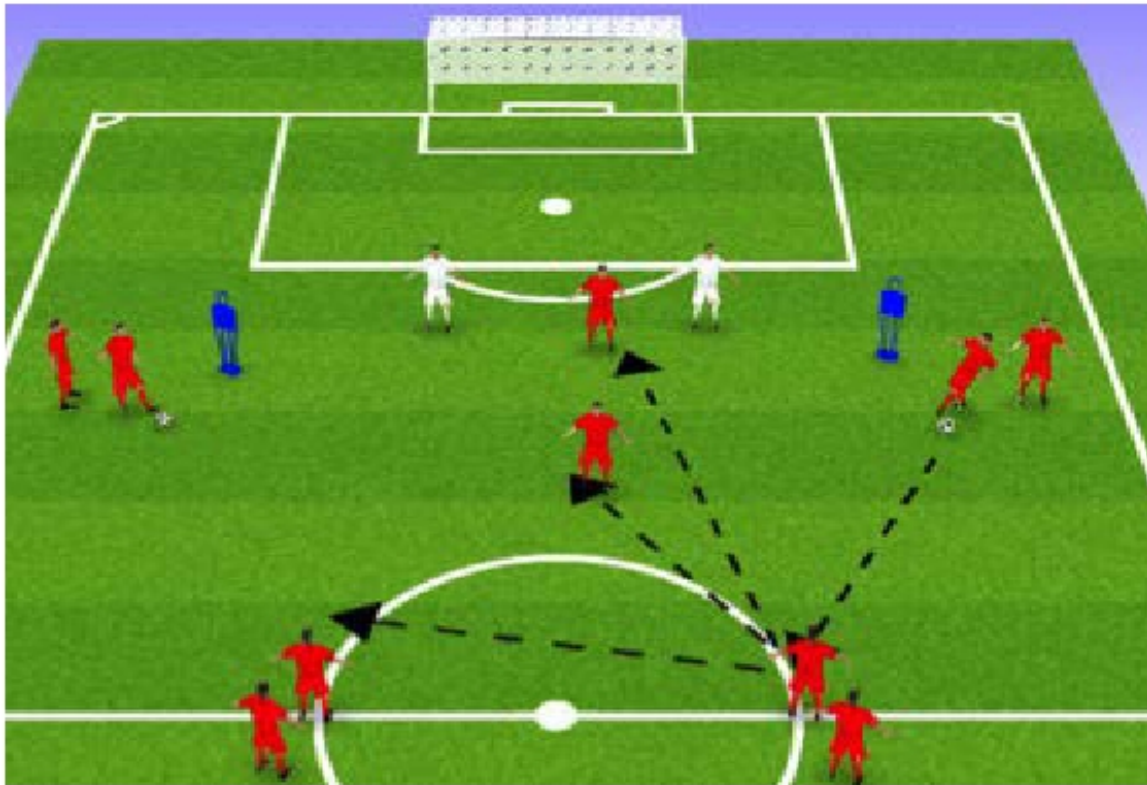
Passing, Receiving, Finishing

Area: Half pitch

Duration: 8 x 21/2 minutes



Attacking Skills, central midfielder receives the pass and distributes to attackers
Area: Half pitch
Duration: 3 x 4 minutes, 1 x 3 minutes



Transitions, goalkeeper passes to defenders who then play into attackers
Area: Half pitch
Duration: 11 minutes



Movement Pattern 4 v 4 + 2, midfield receives the ball and distributes to attackers
Area: Half pitch
Duration: 6 x 2 minutes



8 v 7 Opposite Movement, defender passes to forward who distributes play
Area: Half pitch
Duration: 10 minutes



Finishing, midfielder receives the ball and distributes to attackers
Area: Half pitch
Duration: 4 x 2 minutes



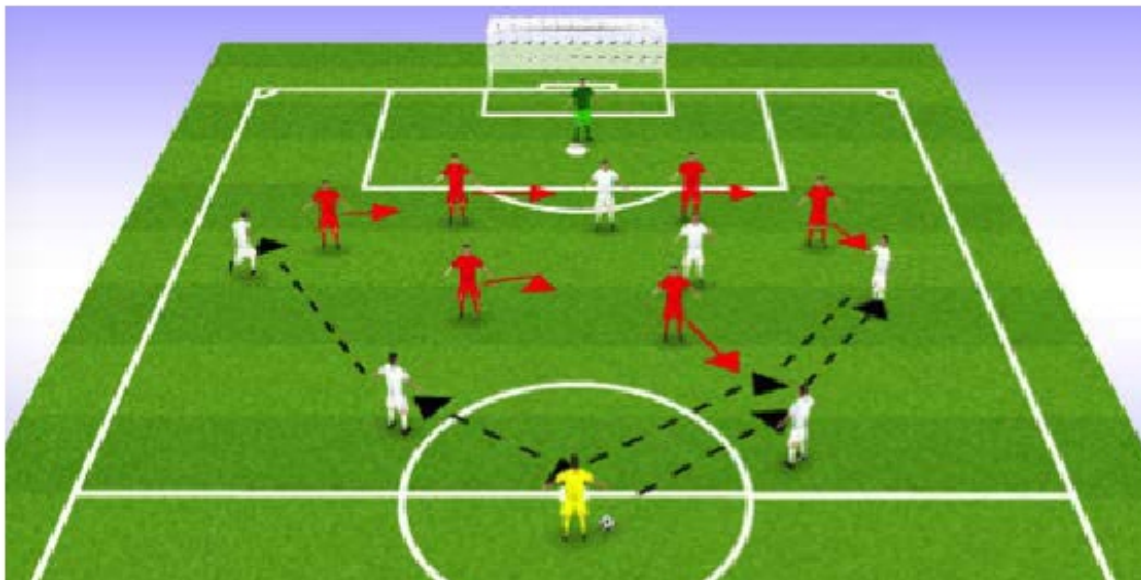
Movement Pattern, ball played to #4 or #5 who distribute ball to #9 and #10
Area: Half-pitch x 36 metres
Duration: 1 minute; 3^{1/2} minutes; 4 minutes; 4^{1/2} minutes



Finishing, pass to #10 who strikes ball (right and left side)
Area: Around 18 penalty area
Duration: 6 x 2^{1/2} minutes



Defensive Shape 6 v 6
Area: Half pitch
Duration: 3 x 4 minutes



Movement Pattern

Area: Half pitch

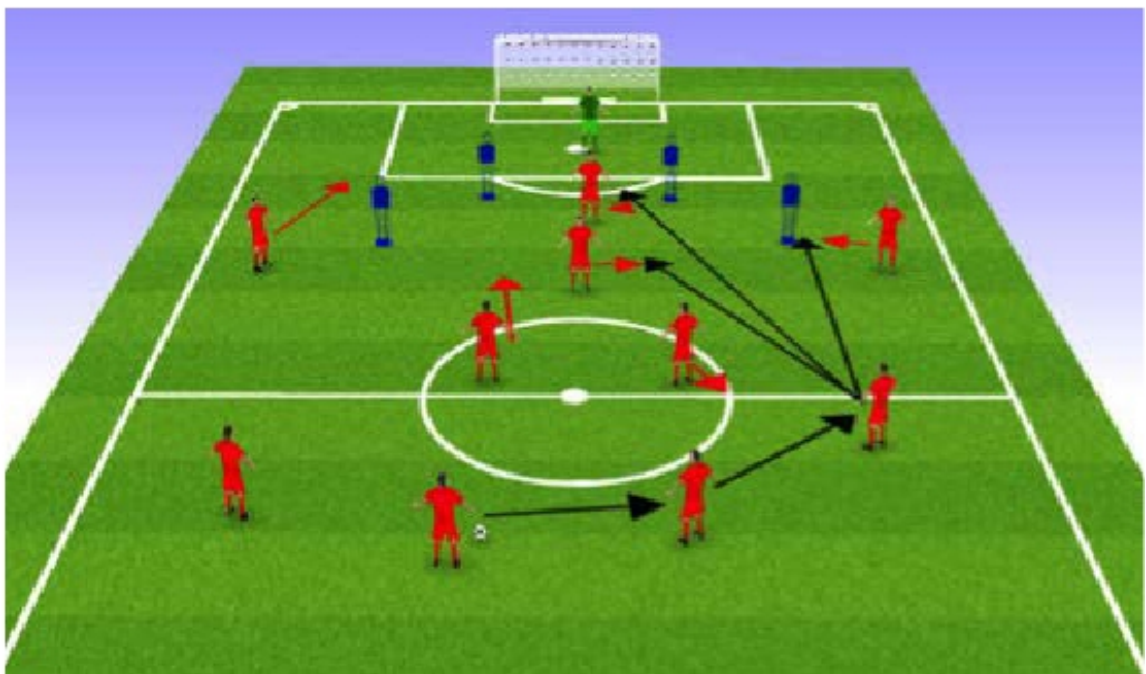
Duration: 10 x 21/2 minutes



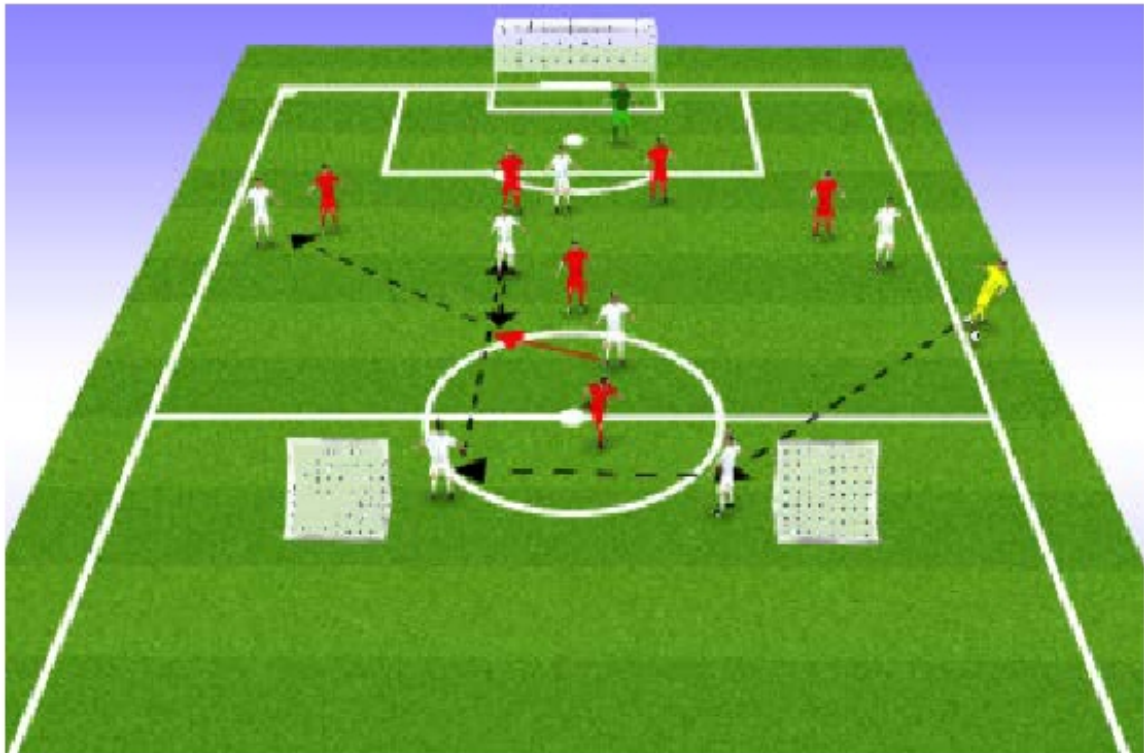
Movement Pattern, level 3 passing through each line

Area: 2/3 pitch

Duration: 5 x 3 minutes



Game Related Drills
8 v 6 Game Related Overload
Area: 36 metres x 36 metres
Duration: 12 minutes



3 v 2 Overload
Area: Half pitch
Duration: 8 minutes; 3 minutes; 4 minutes



Finishing, passing pattern

Area: Half pitch

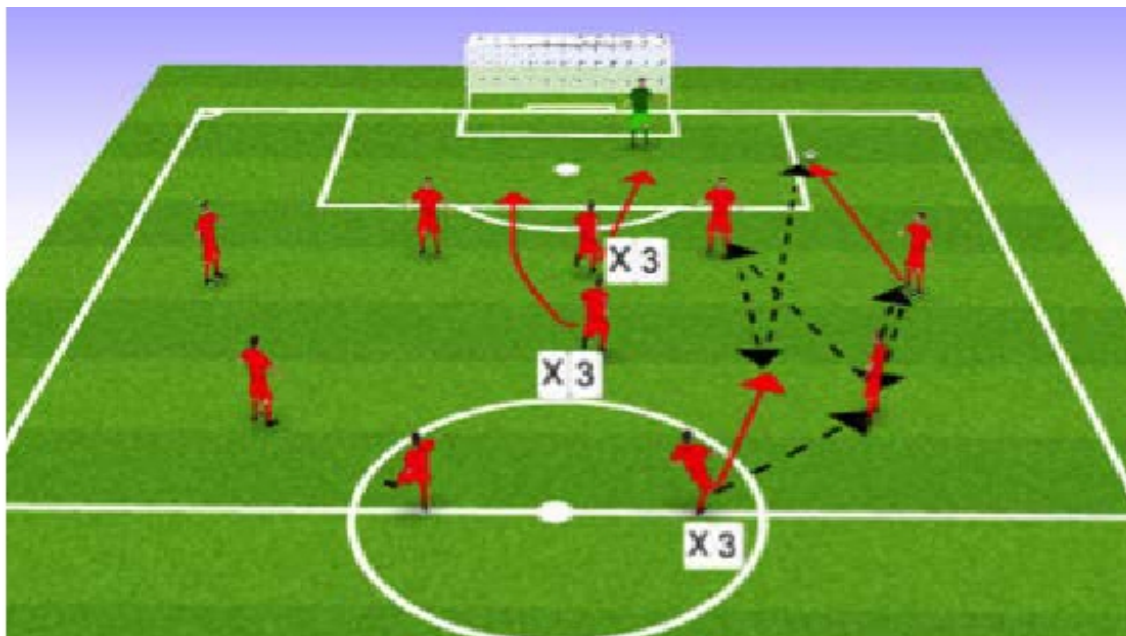
Duration: 2 x 2 minutes; 3 minutes; 4 minutes



Passing, Receiving, Finishing

Area: Half pitch

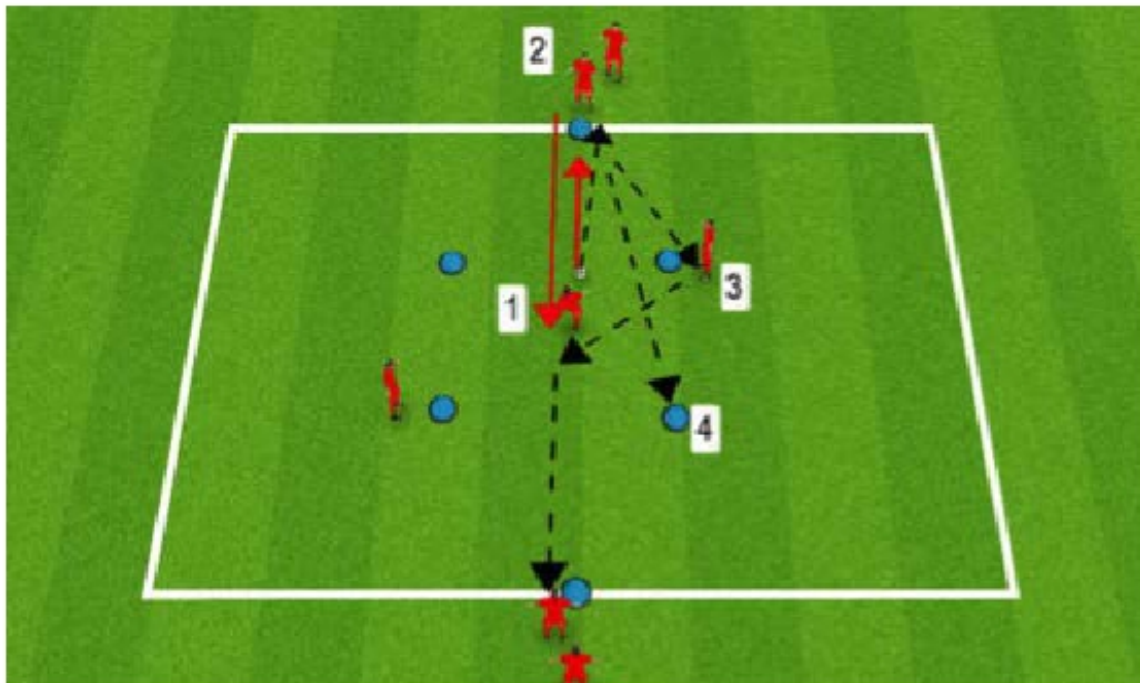
Duration: 8 x 2^{1/2} minutes



Passing and Receiving

Area: 26 metres x 16 metres

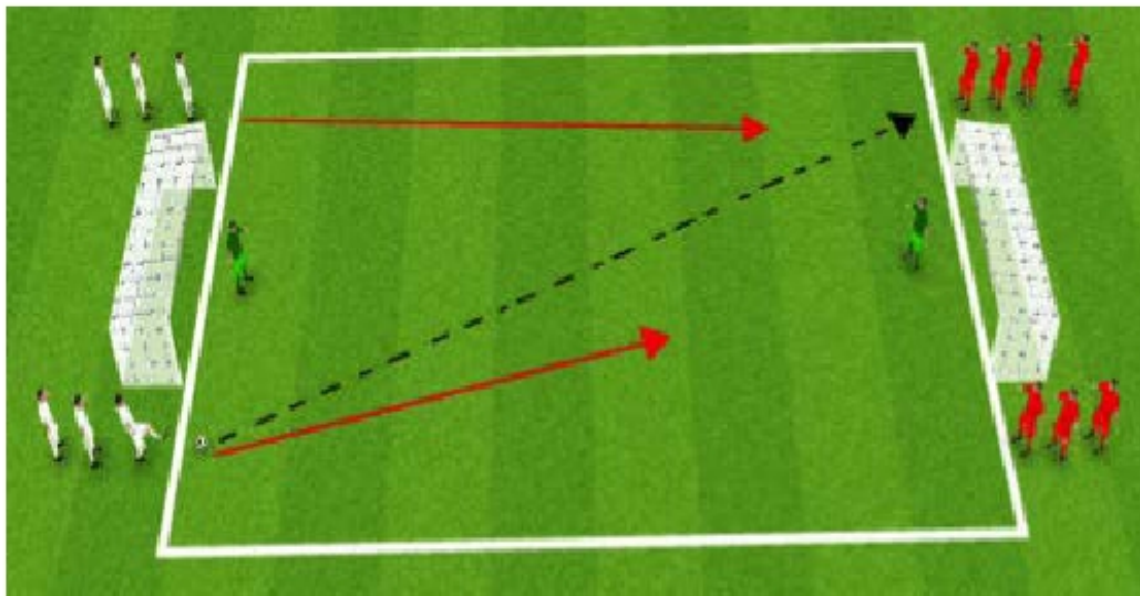
Duration: 3 minutes; 2 x 2 minutes; 1 minute



2 v 2, team plays pass and then defends

Area: 30 metres x 28 metres

Duration: 6 minutes; 5 minutes



3 v 2, defender passes to attacker to create overlap
Area: 30 metres x 30 metres
Duration: 3 minutes; 2 minutes; 5 minutes



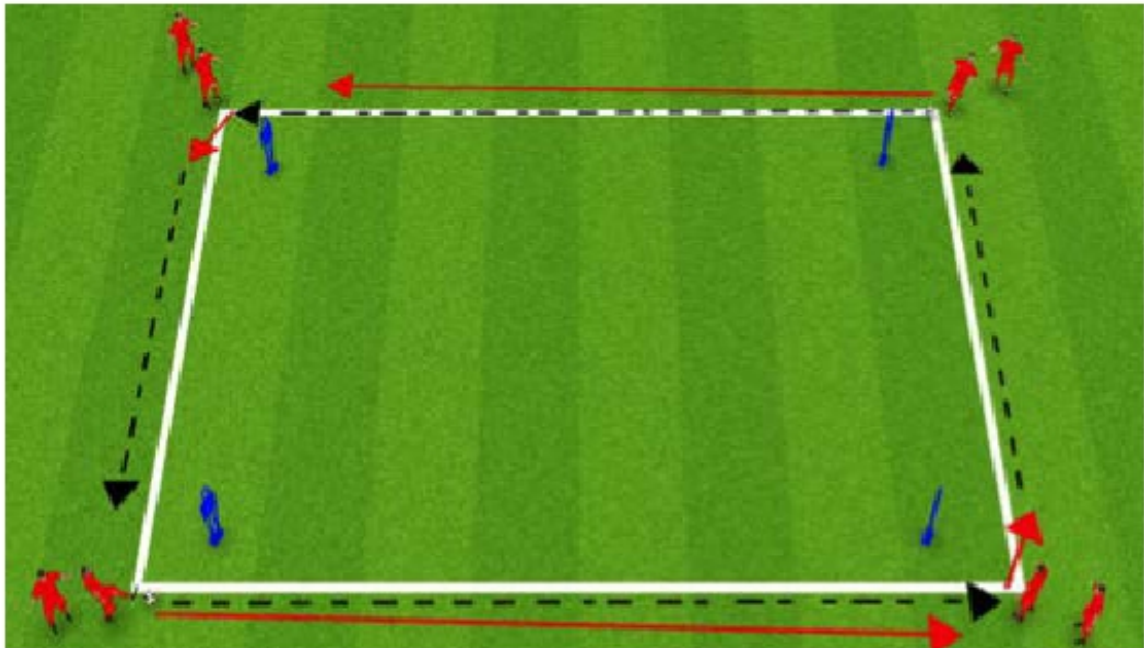
Finishing, midfielder passes to #10 who distributes to # 9
Area: Half pitch
Duration: 2^{1/2} minutes; 3 minutes; 3^{1/2} minutes; 5 minutes



Passing and Receiving

Area: 19 metres x 14 metres

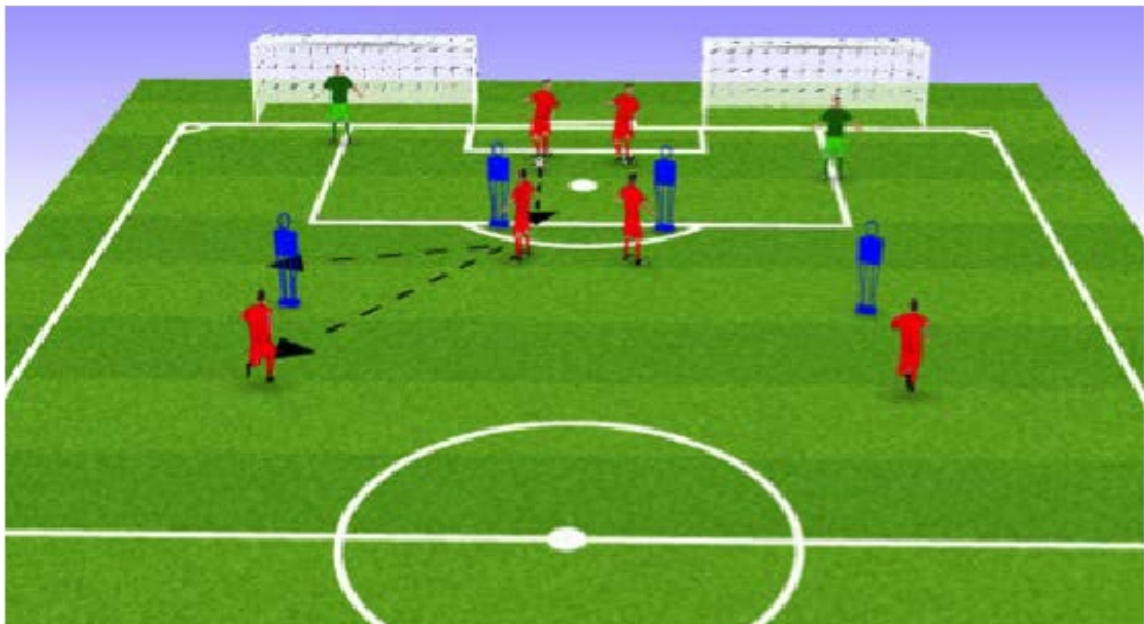
Duration: 6 x 1^{1/2} minutes



Finishing

Area: 38 metres x 22 metres

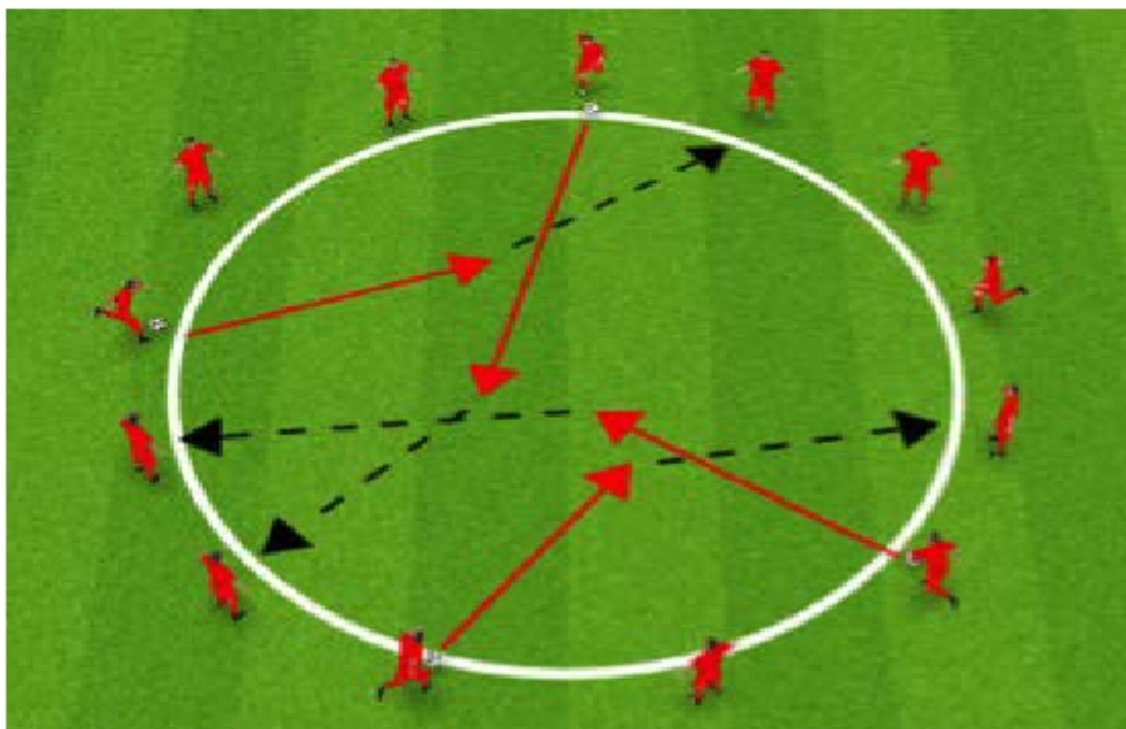
Duration: 14 minutes



Passing and Receiving, right and left

Area: 42 metres

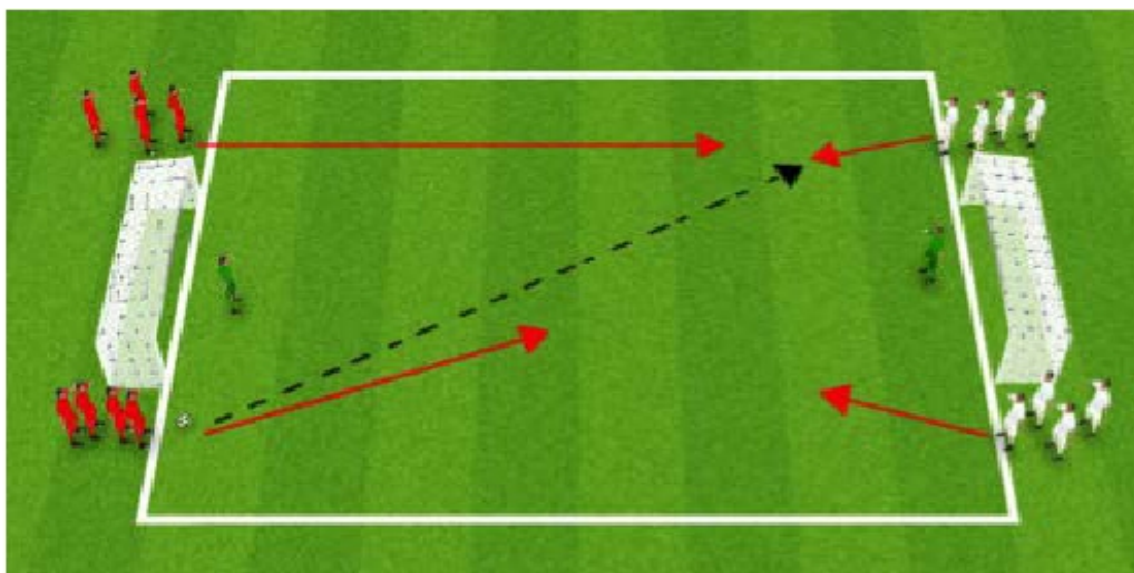
Duration: 12 minutes



2 v 2, diagonal pass then defending

Area: 34 metres x 33 metres

Duration: 9 minutes



Shooting

Area: Outside penalty area

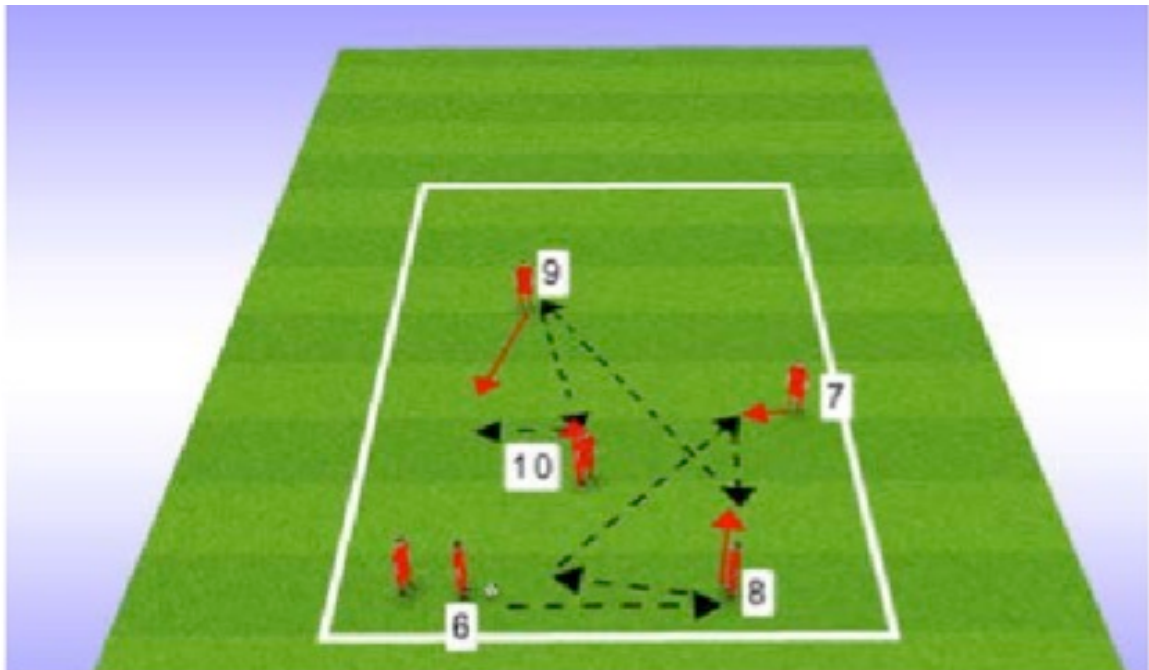
Duration: 6 x 3 minutes



Transition, one touch passing

Area: 20 metres x 10 metres

Duration: 3 x 2 minutes; 2 x 3 minutes; 4 minutes



Small-Sided Games

7v7

Area: 36 metres x 34 metres

Duration: 2 x 8 minutes



6v6

Area: 36 metres x 34 metres

Duration: 3 x 5 minutes



4v4

Area: 36 metres x 34 metres

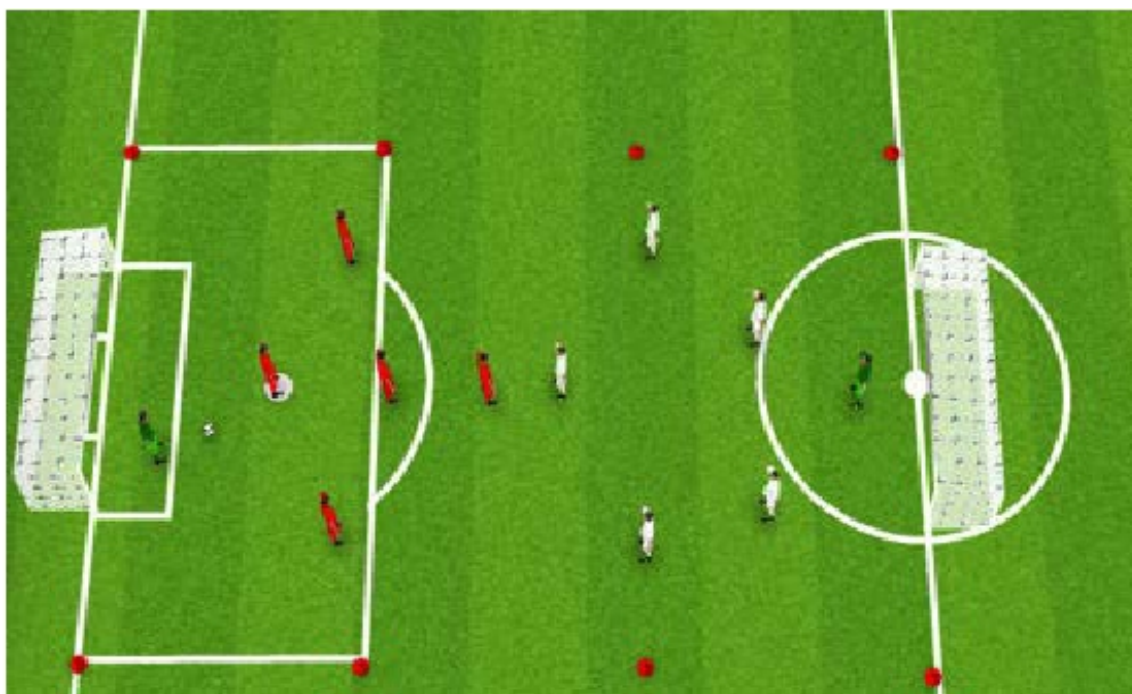
Duration: 2 x 5 minutes



8v8

Area: 50 metres x 50 metres

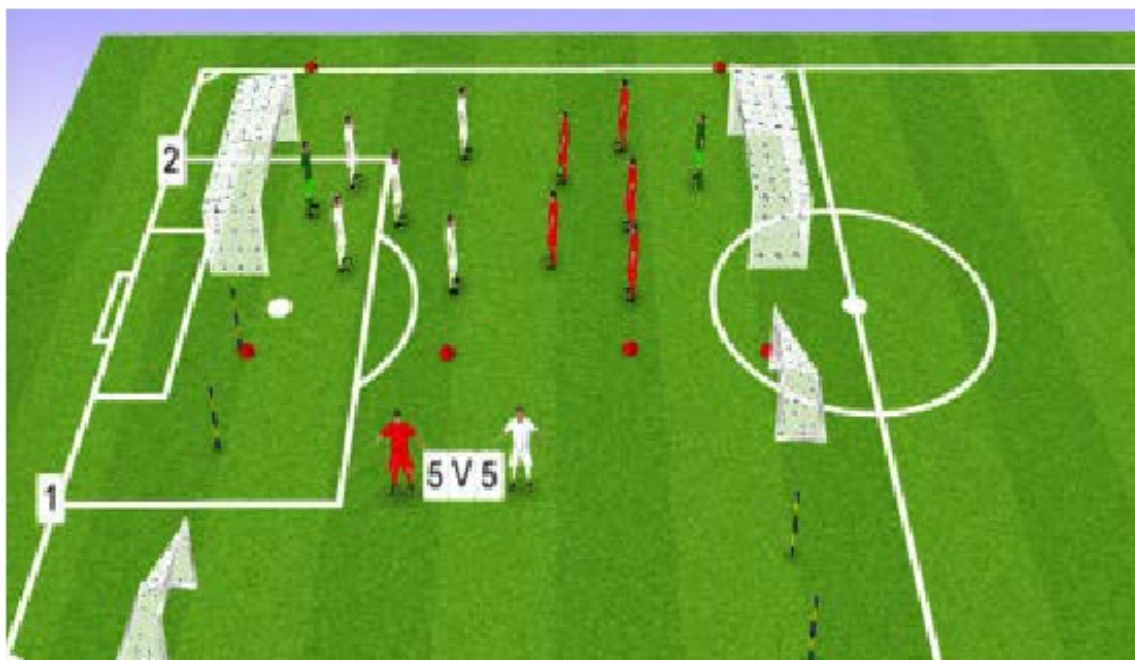
Duration: 8 minutes; 10 minutes



5v5

Area: 43 metres x 48 metres

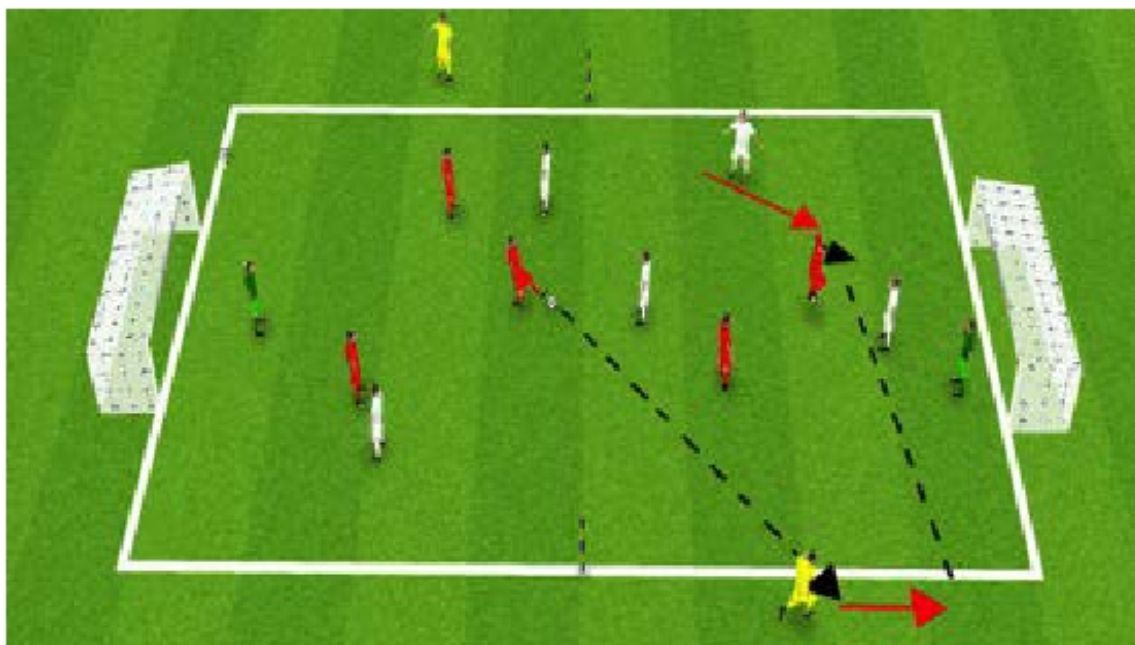
Duration: 4 x 2 minutes



5v5+1

Area: 48 metres x 42 metres

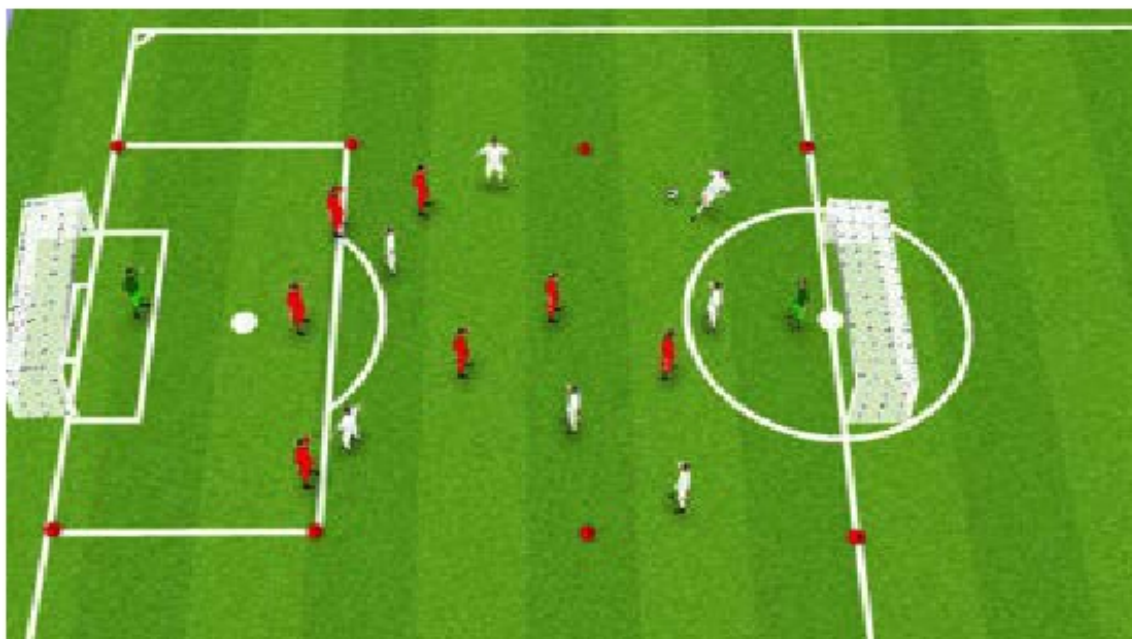
Duration: 6 minutes; 5 minutes; 7 minutes



7v7

Area: 36 metres x 36 metres

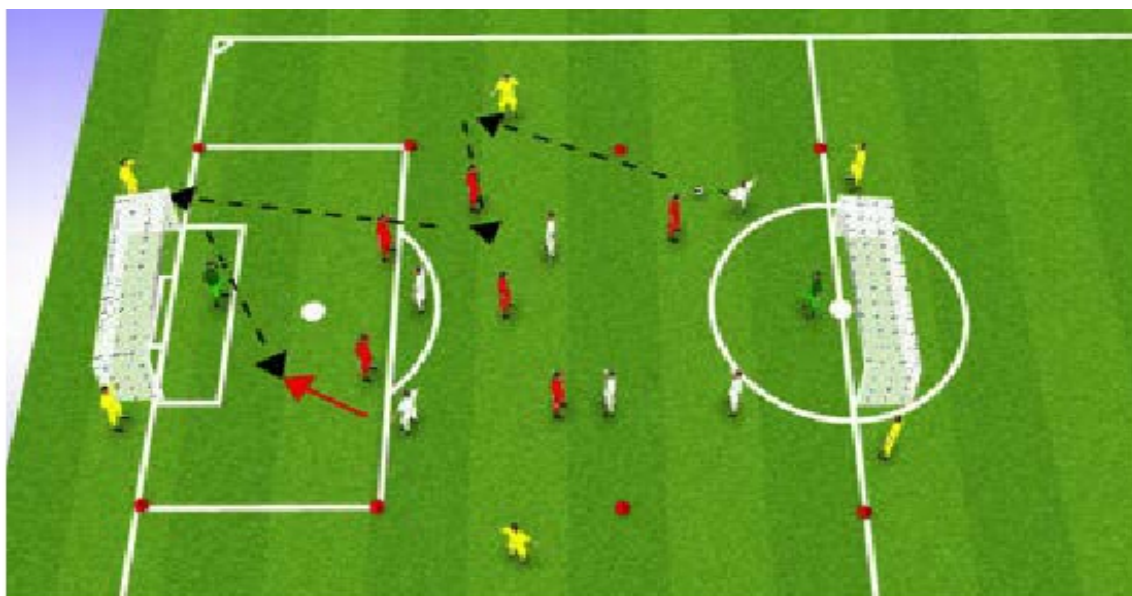
Duration: 5 minutes; 3^{1/2} minutes



6v6+6

Area: 40 metres x 35 metres

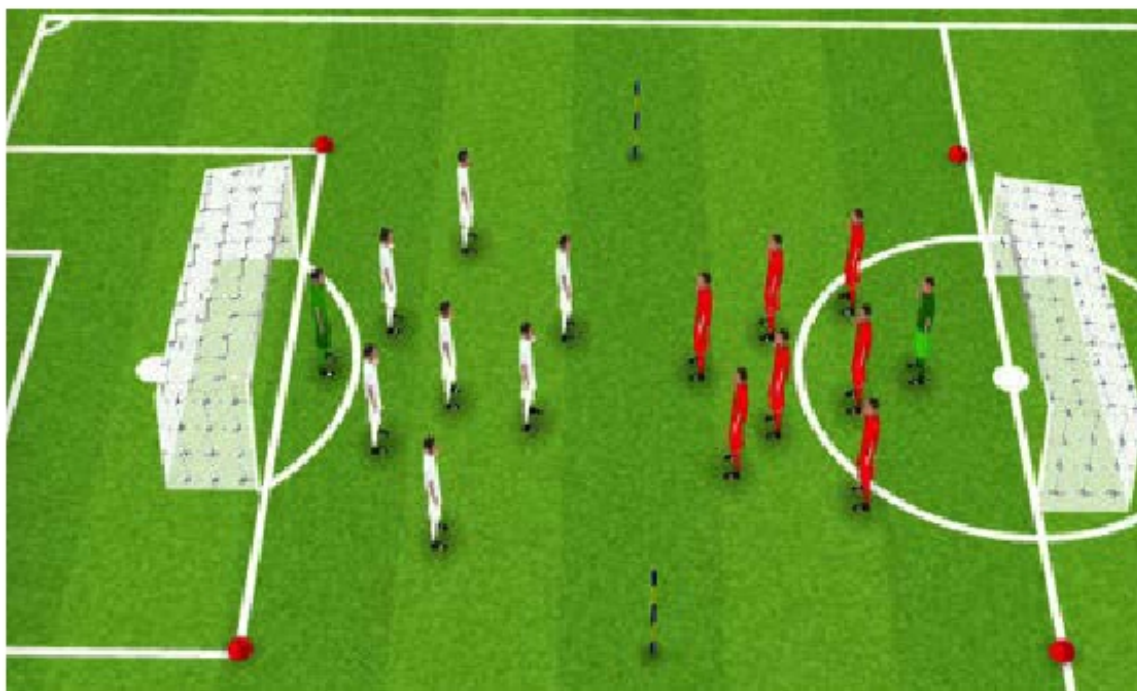
Duration: 4 x 2 minutes



8v8

Area: 46 metres x 48 metres

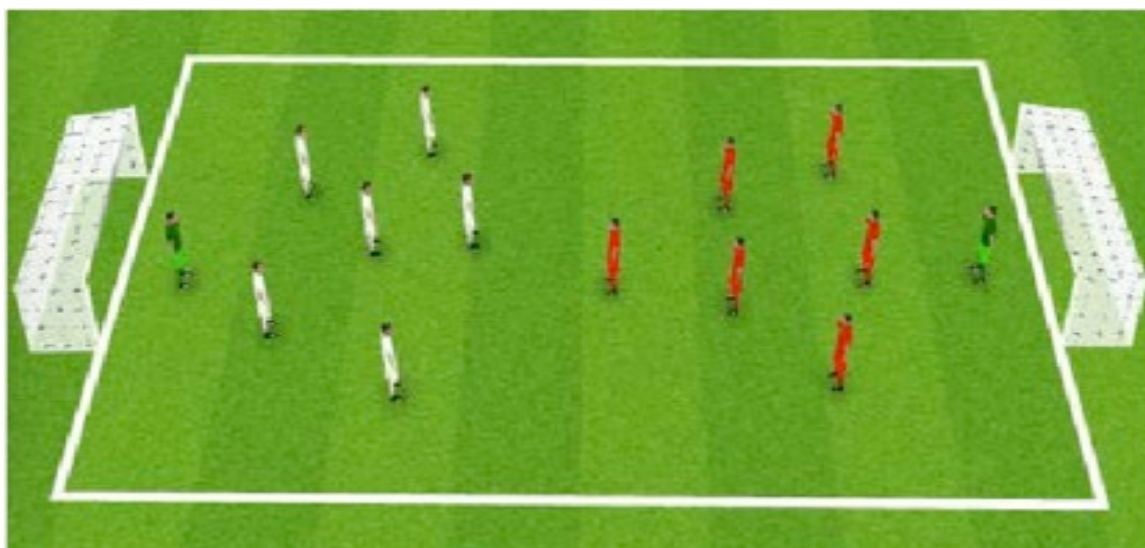
Duration: 2 x 6 minutes; 5 minutes



6v6

Area: 40 metres x 34 metres

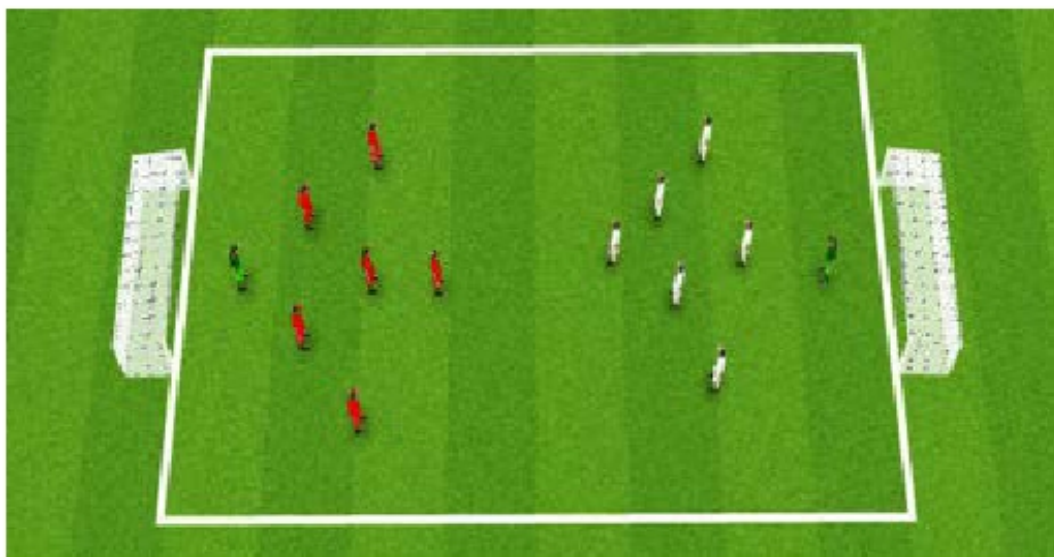
Duration: 2 x 6 minutes



6v6

Area: 43 metres x 48 metres

Duration: 4 x 2 minutes



5v5

Area: 40 metres x 40 metres

Duration: 3 x 4 minutes; 3 minutes



7v7

Area: 47 metres x 34 metres

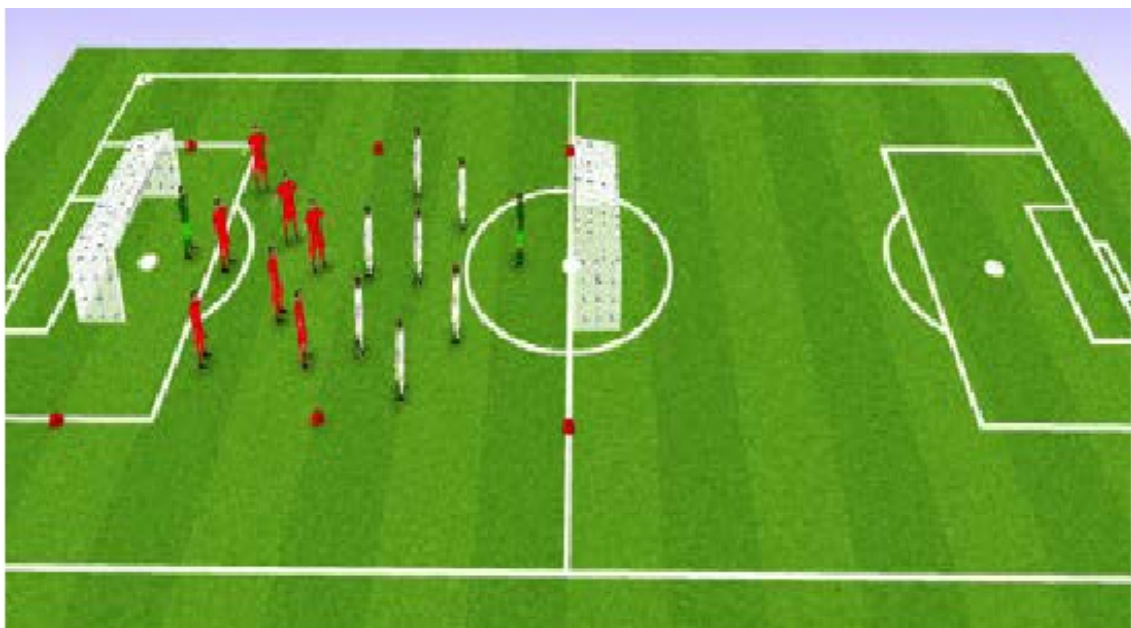
Duration: 4 x 5 minutes



7v7

Area: 29 metres x 48 metres

Duration: 3 x 6 minutes; 4 minutes



Appendix 2

Distance covered (metres) of soccer players of different leagues

Playing Position	Mean Total Distance	Study
Defender	10932 \pm 728 m (UEFA)	Andrzejewski et al., 2012
	10452 \pm 755 m (FAPL)	Bradley et al., 2011
Central defender	9901 \pm 619 m (FAPL)	Di Salvo et al., 2013
	11393 \pm 1016 m (La Liga)	Di Salvo et al., 2007
	10496 \pm 772 m (La Liga)	Dellal et al., 2011b
	10617 \pm 858 m (FAPL)	Dellal et al., 2011b
	10425 \pm 808 m (Ligue 1)	Dellal et al., 2010b
	9885 \pm 555 m (FAPL)	Bradley et al., 2009
	9951 \pm 491 m (NEL)	Terje et al., 2016
Full back	10649 \pm 786 m (La Liga)	Dellal et al., 2011b
	10775 \pm 646 m (FAPL)	Dellal et al., 2011b
	10556 \pm 860 m (Ligue 1)	Dellal et al., 2010b
	10710 \pm 589 m (FAPL)	Bradley et al., 2009
	11426 \pm 648 m (NEL)	Terje et al., 2016
External defender	10639 \pm 609 m (FAPL)	Di Salvo et al., 2013
	11410 \pm 708 m (La Liga)	Di Salvo et al., 2007
Midfielder	11770 \pm 554 m (UEFA)	Andrzejewski et al., 2012
	11505 \pm 783 m (FAPL)	Bradley et al., 2011
Central Midfielder	11487 \pm 727 m (FAPL)	Di Salvo et al., 2013
	12027 \pm 625 m (La Liga)	Di Salvo et al., 2007
	11247 \pm 913 m (La Liga)	Dellal et al., 2011b
	11556 \pm 811 m (FAPL)	Dellal et al., 2011b
	11501 \pm 901 m (Ligue 1)	Dellal et al., 2010b
	11450 \pm 608 m (FAPL)	Bradley et al., 2009
	11573 \pm 768 m (NEL)	Terje et al., 2016
External Midfielder	11496 \pm 821 m (FAPL)	Di Salvo et al., 2013
	11990 \pm 776 m (La Liga)	Di Salvo et al., 2007
	11005 \pm 1164 m (La Liga)	Dellal et al., 2011b
	11780 \pm 706 m (FAPL)	Dellal et al., 2011b
	12030 \pm 978 m (Ligue 1)	Dellal et al., 2010b
	11990 \pm 771 m (NEL)	Terje et al., 2016
Forward	10541 \pm 944 m (FAPL)	Di Salvo et al., 2013
	11254 \pm 894 m (La Liga)	Di Salvo et al., 2007
	10718 \pm 901 m (La Liga)	Dellal et al., 2011b
	10803 \pm 992 m (FAPL)	Dellal et al., 2011b
	10942 \pm 979 m (Ligue 1)	Dellal et al., 2010b
	11377 \pm 584 m (UEFA)	Andrzejewski et al., 2012
	10314 \pm 1175 m (FAPL)	Bradley et al., 2009
	9982 \pm 769 m (FAPL)	Bradley et al., 2011
	10429 \pm 874 m (NEL)	Terje et al., 2016